Thesis

Flight Simulation

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Preface

This thesis[1] contains research and development aimed at providing a better understanding of flight simulation. The topic is presented in a way that should make people understand all the aspects of flight simulation, make them appreciate the evolution of simulation and wonder about its future. At the end of this paper, I raise a few questions that could encourage interested people to find some answers.

During my study at McGill University, I was away from home and from my family that I grew up with. My parents incredibly believed in my choice; studying in Canada. Their trust was and still a big support and it gave me the courage to complete my Master degree. I would like to dedicate my work to my father *Abdul-Hussin* and to my mother *Amneh*. Without them, my work couldn't reach to a complete end. I had a great chance to work with Professor. Gerald Ratzer[2], he supervised my thesis and put his trust in my work which motivated me to work harder and to offer the best of me.

[1] This work has not been funded by any member or staff.
[2] Gerald Ratzer is a Professor at McGill University since 1966

Abstract

Simulation is the technique by which a physical system can be represented mathematically by a computer program for the solution of a problem. This technique of problem solving is used when it is not feasible due to time, cost, or safety to conduct specific tests using the actual physical system, such as an aircraft. A mathematical model is developed for the physical system using knowledge of the physical laws describing the problem. This model is then programmed on the computer to generate the problem solution. The digital computer program represents a discrete approximation of the real world system which is usually continuous. My contribution to this work involves, searching and collecting information, studying a case about environmental simulation, implementing a miscellaneous function that is used by pilots during their training on a flight simulator, presenting the history of flight simulation, writing the conclusion and raising questions at the end. In my opinion, raising question and pointing out problems is as important as finding answers and solutions.

Résumé

La simulation est une technique qu'on peut utiliser pour représenter un système physique dans le but de résoudre un problème donné. Cette technique de résolution de problèmes est utilisée lorsqu'il est impossible, dû au coût, temps ou facteur de sécurité, d'appliquer une série de tests en utilisant le système physique actuel, e.g. un avion. Un modèle mathématique est développé pour simuler le système physique en utilisant des lois physiques qui décrivent le problème. Ce modèle est implanté pour trouver des solutions. Un programme digital représente une approximation discrète du système du monde réel qui est normalement continu. Ma contribution à ce travail inclut: la recherche et la collecte d'information, l'étude de cas décrivant la simulation environnementale, l'implantation d'une fonction utilisée par des pilotes pendant leur entraînement sur le simulateur de vol, la présentation de l'histoire de simulation de vol et la rédaction de conclusion.

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Chapter 1

1. Introduction.

This paper is intended as a complete document summarizing the history, the advantages and uses of flight simulation, describing some of the current technology available, indicating how and why it works, and summarizing the potential future for flight simulation.

The term "simulation" is used rather broadly today to cover several concepts in the computing world. This document deals specifically with "real-time" simulation. The term "real-time", as it relates to simulation, requires that the computer program execution of a modeled, dynamic process must occur in the real-world time (i.e., not faster or slower). It represents or simulates a real, dynamic phenomenon as it occurs. A real-time simulation flight vehicle is usually characterized by a cockpit, interface hardware, computers, and a pilot, all of which are linked together in a closed loop system.

1.1 Advantages of Simulation.

There are many advantages of using simulation in lieu of other methods of research. For example, expensive prototypes need not be built and possibly destroyed during flight tests. A real vehicle (aircraft or spacecraft) with humans aboard need not be used for unknown experimental results thus jeopardizing life and expensive equipment. With simulation it is easy to extend the testing beyond the normal safety thresholds. Simulation permits rapid change from one set of conditions to another in a controlled environment, thus greatly extending the versatility of an experimental setup. Real-time simulation allows a more realistic representation of the physical system being studied (as opposed to pure mathematical analysis or standard computer analysis) and permits both quantitative and qualitative (human analysis) evaluation. In addition, pilots can be trained for various operational concepts without using expensive vehicles.

1.2 Simulation Computers.

All real-time simulation computers have the capability of running real-time programs simultaneously with batch and interactive processing. Real-time programs are allocated their own (dedicated) Central Processor Unit (CPU) to run on and the non real-time computational programs are run on the remaining platform CPU's.

1.3 Open Shop Versus Closed Shop.

Another unique aspect of real-time simulation is that the implementation and operation of a study is normally done in a closed shop[1] environment. This means that the majority of the program development, simulator development, and interfacing of software and hardware is done by open shop and not by the researcher. Open shop is also responsible for the modifications, verification, and operation of the simulation. Since real-time simulation is a specialized field that requires a combination of knowledge and experience in real-time concepts, computer system operations, and simulator hardware, it is highly recommended that the closed shop policy be adopted by the researcher unless circumstances justify otherwise. Similar areas of importance are numerical analysis, aerodynamics, and computer science, as well as specific knowledge of several types of computers and programming languages. This is in contrast to the open shop environment that exists for non real-time simulation where the researchers do programming through workstations or interactive terminals. [24,25]

[1] Closed shop involves work that is dedicated for research purposes

1.4 Batch Processing.

When the control inputs to the system can be predetermined and are programmable, batch processing of the simulation program is possible. For batch processing, the computer program is submitted to the computer complex for the running of one or more test cases. The program is run as fast as the computer will allow. Here the problem time in the computer program (as it is running) is not related to the real world time.

1.5 Pilot-In-The-Loop.

In the event that the control inputs necessary for the testing procedure are dynamic in nature or cannot be predetermined, such as the pilot response in an actual aircraft, the term simulation takes on a new dimension known as real-time simulation. This new dimension calls for strict correspondence between the computer problem time (as it is running) and the real world time. Inputs and outputs to hardware devices must be synchronized to a real-time clock and cannot be time-scaled as in the batch computing environment. A typical aircraft simulation involves a real-time computer program, a pilot, a cockpit, and appropriate interfaces that are all synchronized and running in real world time. A real-time simulation of the aircraft corresponds to an actual aircraft flight as viewed by an observer. When an actual piece of flight equipment such as a control device is placed in the simulation, then the simulation becomes hardware-in-the-loop with the same characteristics as pilot-in-the-loop.

1.6 Time Critical Processing.

The real-time execution of a computer program requires the use of special software in connection with the computer operation. The program execution must be synchronized with the real world time, i.e., the change in computer problem time must correspond to an identical change in real world clock time. A real-time clock is incorporated in the computer system and used by the special software. The clock system divides the computer operation into equal intervals of time by synchronization pulses. These intervals of time are called frame times and are fixed for a given simulation. During a frame time the computer program is solved and the computer problem time is incremented by the frame time value.

In real-time simulation, we are capable of running multiple real-time programs simultaneously on one HP/CONVEX computer for example, with each program allocated to its own (locked down) CPU. The frame time for each real-time computer program is divided into three sections: (1) input - computer program inputs are updated; (2) computer program calculations or solution; and (3) output - computer program outputs are updated. The remaining CPU's are used for other real-time simulations, as well as interactive and batch processing.

The necessary CPU frame time to calculate an update and satisfy the problem sample rate is requested or scheduled by the programmer for the computer job. The frame time is typically a multiple of 125 microseconds and the iterations per second (sample rate) is the inverse of the frame time. The update changes the computer problem time by an incremental amount (normally equal to the frame time) and the problem is updated at the specified sample rate. As the problem frequencies increase, the sample rate per problem cycle decreases (for a fixed frame time). As one can see, excessively high problem frequencies can result in an inadequately low sampling rate. The effect of sampling rate can be checked by comparing to a batch program or by halving the problem time increment (time scaling) and comparing the results.

1.7 Characteristics of Flight Simulation.

Technical advances over the last 20 years have made flight simulation particularly effective in modeling the flight environment, and it is now an integral part of the aviation scene in the civil, military, manufacturing, and research fields. Compared to the flight environment, simulation gives close control of the conditions under investigation, and allows specific flight situations, some of which are rare or hazardous, to be available on demand. Compared to the use of aircraft for these activities, simulation causes no environmental pollution, noise or other disturbance. For all but the simplest aircraft, flight simulation is also substantially less expensive than use of the aircraft itself. Finally, simulators can be used at intensive rates of operation by day and night, and can carry out any exercise or function which is included in their data base irrespective of location, weather, time of day or season of the year. [20,27]

1.8 Pilot Training.

Flight Simulation is an effective means for personnel to acquire and maintain the skills required for the operation of civil and military aircraft. Training may be accomplished in simulators for exercises which are neither possible nor safe in the actual aircraft, including the practice of emergencies and failure cases, training for adverse weather conditions, and familiarization with airports which have special takeoff, approach or landing procedures. In civil aviation, conversion of experienced pilots to a new type of aircraft can be conducted entirely in a flight simulator of appropriate standard. This has been called "zero flight time conversion" and is many orders less expensive than the use of the aircraft itself for conversion training; it is also safer when dealing with exercises such as engine and other failures. In the military field, satellite and other data may be used to produce realistic visual scenes of any location, mission rehearsal training is possible for areas anywhere in the world.

1.9 Other uses of Simulation Technology.

In addition to the training of pilots in flying the aircraft, flight simulation has an invaluable role to play in other aeronautical areas, such as research, accident investigation, aircraft design and development, operational analysis, and other activities such as space flight and simulations of conflicts involving many players. The latter includes whole battle scenarios and multiple air combat. Such simulations can indicate tactics to be employed, or where design effort should be concentrated for maximum effect in the future. In space flight, many hundreds of simulation hours support each crew member for every launch. Research areas, as well as covering battle scenarios, include new concepts, new systems, flying qualities, and human factors. Most aircraft manufacturers use research simulators as an integral part of aircraft design, development and clearance. Major aeronautical projects would now be impractical without the extensive use of flight simulation, on both cost and safety grounds. It should also be noted that similar technology in systems such as visual and motion, is now being used in the simulation of motor vehicles, trains, Armoured Fighting Vehicles (AFVs), ships and submarines.

1.10 The principles of flight simulation.

The main elements of a flight simulator are the cockpit, motion system, visual system, computer, and instructor/operator station. The cockpit provides a suitable environment for the crew in terms of the location, appearance, and feel of controls and displays. It may be mounted on a hydraulically operated motion platform, capable of imparting to the crew the impression of aircraft movement, adding to the fidelity of the observed response to flight control inputs and external disturbances. Motion cues are particularly important in critical handling tasks, and during instrument flight. The visual system presents the view seen by the pilot of the external visual scene. Advanced technology is needed to achieve representative scene details over a large field of view. The computer must process in real time the mathematical models which represent the aircraft, its systems, and the operating environment. It receives signals from the cockpit, and provides inputs to the other elements in the simulation.

1.11 Motion Cueing.

The various motion sensors in the human body essentially act as accelerometers but have thresholds below which accelerations are not detected. Therefore, they do not provide accurate information of velocity and rates of travel such as rates of turn; hence the need for blind-flying instruments in aircraft. These human characteristics are exploited in the mechanization of simulator motion systems, to compensate for the limited travel of the motion platform. The technique is known as "acceleration onset cueing", and is equally effective in the simulation of motion and manoeuvre for agile fighter aircraft as well as helicopters and airliners. For fighters, the simulation of high `G' forces leaves something to be desired but cueing for high G can be obtained by the use of the pilot's G-suit in the simulator, by the use of specially designed simulator G-seats, and by the use of features such as the progressive dimming of the visual system under very high simulated G. Meanwhile, the use of a modern high quality motion platform enables good fidelity to be achieved both for the atmospheric environment (turbulence, wind shear etc.) and for simulator responses to flight control inputs by the pilot. With a high quality motion platform, realistic training in aircraft handling is thus possible, particularly in critical areas of use of controls, such as in turbulent conditions, failure cases, and in areas of flight where external visual cues are reduced such as at night, under reduced visibility, instrument flying generally, and, for the military, flight using electro-optical sensors. The quality of the motion cues is important; false cues can result in a situation where no motion cueing would be preferable; no motion is preferable to poor motion. However, modern motion platforms have feedback and diagnostic systems in order to record and sustain their performance. Under civil regulations, only devices with motion platforms are categorized as flight simulators; those with fixed bases are known as training devices and do not attract credits for the higher levels of training activity.

1.12 Visual Cueing.

There are two components to a flight simulator visual system; the image generator, and the display system. Image generation uses digital processors of high speed and large capacity to create the visual scene. Information about the terrain contours, nature of the terrain, and cultural features is stored in the image generator. The information may be either generic, or based on actual locations using digital mapping data. The information is sifted to isolate the area of immediate interest, and then processed to give the correct aspect from the viewing position, correct relationship between objects in the scene, color, visibility, and lighting. The refresh rate of the display is critical; low refresh rates do not provide sufficient information for rapid crew response to critical situations. The display system may use projectors which magnify information displayed on high quality TV screens to illuminate a wide angle screen which surrounds the cockpit, or use a focusing system to present the images as if they were at large distances. The latter system is favored on civil airline simulators, where the field of view requirements are less demanding than those of the military and it is required to simultaneously present the same perspective to both pilot and copilot.

1.13 Coordination of Motion and Visual Cues.

Since the motion sensors in the body act as accelerometers, this contrasts with visual cues which depend on angular or translational displacements. An acceleration must occur first before a displacement may be noted; in consequence, after a control input or an external disturbance such as atmospheric turbulence, the resulting motion cues are received by the brain before the visual cues for the same disturbance. Motion cues are therefore particularly important where a prompt pilot response may be required, or under any conditions involving limited external visual cues. Correctly sequenced motion and visual cues are essential if fidelity of aircraft handling is to be achieved in a flight simulator. There have been number of cases of what has been termed `simulator sickness' which can vary between symptoms of slight disorientation to nausea, both while in the simulator and also for some hours afterwards. This is generally due to a combination of personal susceptibility and poorly coordinated motion and visual systems. It is greatly reduced in modern flight simulators which have fast-reacting motion platforms and high quality control, backed up by monitoring systems and automatic test programs which keep the systems in tolerance. Finally, simulations which use wide-angle visual systems presenting high-density scenes over large areas, if used without a correctly coordinated motion platform, cause subconscious cue-conflicts in the crew under training because of the lack of the real motion cues which would be present in the aircraft, and have also led to cases of `simulator sickness'.

1.14 Modeling.

The degree to which the aircraft and its environment can be represented is dictated by the nature of the aircraft and the speed and capacity of digital computers. Agile military aircraft are the most difficult to model. The requirement is to minimize time delays between a pilot's control input and the responses felt and then seen by the pilot. Improvements in computing speed and power help this situation, and allow more complex models to be used. Not only can the aircraft itself be modeled more accurately and in greater detail, such factors as the air mass and its behavior, the ground and its interaction on the aircraft, and the presence and interaction with other aircraft and vehicles can be included in the simulation.

1.15 The benefits of training by simulation.

The benefits which accrue from using ground-based simulators rather than in-flight training are difficult to quantify exactly in terms of enhanced safety and quality of training, but have been generally proven over many years. However, simulators are much cheaper to operate than all but the simplest aircraft and so there is a strong economic case for their use. They are frequently used on a continuous 24 hour training cycle at an intensity of training far in excess of that achievable by the use of the aircraft itself in the training role. Aircraft are constrained by weather, simulators are not, and furthermore can train for any condition at any time. In a simulator, night flying can be trained during the day, winter conditions can be simulated at any season, a takeoff or landing at Sarajevo (or anywhere else in the simulator's data base) can be flown while still at the simulator's location, and critical training conditions such as takeoff and landing in limiting crosswinds or in severe turbulence (e.g. microburst conditions) can be produced in the simulator at will.

1.15.1 Civil Aviation.

In the case of airlines, the use of flight simulation training allows a reduced size of aircraft fleet because no longer is it necessary to earmark aircraft themselves for extensive crew training. The cost of operating an airliner on training is also many times more than purchasing and operating a flight simulator, and in addition takes the aircraft out of revenue service. In addition, training using the aircraft itself is not possible at crowded airports such as Heathrow, and the costs and time delays of deployment to other airfields for training exercises have to be taken into account. Airports such as Hong Kong, Katmandu, Bern and Innsbruck have special procedures due to potentially dangerous terrain, and other busy airports such as Kennedy (New York) and Dulles (Washington) have special procedures due to congestion. A simulator can show realistic visual scenes of Heathrow, Hong Kong or any other airport and its surrounding terrain and navigational beacons, and so can be used for world-wide training without these constraints.

1.15.2 Military Aspects.

The military case is somewhat different. Force sizes are either limited by budgets or are designed to provide a defined capability should conflict be threatened. Military pilots need to fly the aircraft itself for a minimum number of training hours per month in order to maintain operational readiness and thereby to pose a credible deterrent to a potential adversary. Also, there are aspects of military flying which cannot be reproduced well enough in a flight simulator to give full training value, although a simulator can be used for familiarization and procedural training before continuing on the aircraft itself. Examples, where substantial real flying practicing the tasks is needed, include low flying technique, particularly in rugged terrain, and air combat particularly where high manoeuvre rates and `G' loading are concerned. However, there are several simulation devices which can give cues for high G forces. The military case for the use of more flight simulation training has been strengthened by the complexity of modern military operations with expensive weapon systems. Some scenarios involving, for instance, multiple forces and electronic warfare, simply cannot be trained in the aircraft itself in peacetime; even sophisticated air exercises will fall short of a realistic combat scenario. Not only can such aspects be covered using flight simulation, but simpler procedural aspects also can be trained effectively, including matters which would be too expensive or dangerous to train in the air in peacetime, such as weapons procedures, switching, firing and jettison of stores. There are also factors such as the cost of deployment of aircraft to geographical areas where intrusive training such as low flying is still permitted, public support for environmental issues, and the need in an uncertain world for realistic training for possible operations in areas where no real flying is possible until orders are given to deploy for action. For example, a modern flight simulator could be used for realistic training for possible operations in, for example, Bosnia, well before orders were given to deploy the aircraft. Such training would include detailed visual scenes of the terrain, possible targets, and of both friendly and hostile activity as predicted by intelligence sources and inserted in the simulator's data base. Finally in the military scene is the high cost of using the aircraft itself for routine training such as procedural instrument flying or familiarization with different airfields and their procedures. This can be trained very effectively on a modern simulator with good quality motion and visual systems, and the saving in flying hours may be used to fund a good standard of simulator which can then also be used for the other operational activities mentioned earlier. [24,25] For additional information, the reader may refer to [2,5]

1.16. National and international regulation of flight simulators.

In most of the leading aviation nations, the standard of flight simulators used for the higher levels of civil training is subject to close control by the national aviation regulatory body. In the UK, this body is the Civil Aviation Authority (CAA), in the USA, the Federal Aviation Administration (FAA), in Germany, the Luftfahrt Bundesampt (LBA), and so forth. In the general training of individual pilots, appropriate training exercises and flight checks or tests may be carried out on approved simulators instead of in the aircraft itself, depending on the nature of the exercise, the experience of the pilot, and the type of simulator or trainer concerned. Such exercises conducted under these highly controlled conditions are said to gain "credits" towards the appropriate qualification, in lieu of aircraft flight time. The highest level currently approved for this simulator training is the so called "zero flight time" conversion where it is possible for an already experienced airline captain to convert to a similar aircraft type entirely on a high quality simulator, flying the aircraft itself for the first time on a revenue flight but under the supervision of a captain already fully type qualified. Simulators approved for "zero flight time" training not only have to be built to certain quality standards, but they also have to have the appropriate level of motion and visual systems; they are not only independently checked by the regulatory body after manufacture, but are regularly re-checked to ensure that they continue to match the real aircraft characteristics in the critical areas for training. Lower conditions apply to simulators and other training devices which are used together with the aircraft itself. The regulations for simulator training "credits" have been developed over many years and have kept pace with developments in flight simulation such as improved visual systems and rapid-reacting large throw hydraulic motion platforms; they have therefore been generally uncontroversial.

The FAA and CAA Levels are largely compatible with one another. Level 1 through 4 in the CAA equating with Level A through D in the FAA categorization.

One large difference is that the CAA permit Zero Flight Time training on a Level 3 FFS as well as Level 4, accepting that a daylight visual system is not a requirement for ZFT, whereas the FAA require daylight and hence restrict ZFT to Level D. The level 4 requirement briefly defines the configuration of an acceptance CPT. The requirements for the periodic resetting to maintain the approval are similar to those of the FAA but are, generally, carried out only once every 12 months as opposed to the FAA requirement that inspections shall take place every four months or with their agreement every six months.

In 1989 the Royal Aeronautical Society (RAeS) established an international working group (IWG) chaired by a member of the RAeS Simulation Group Committee, with representation from industry, airline operators, and national regulatory bodies. The intention was to draft an international standard for the acceptance of flight simulators, using the RAeS connection in order to establish a neutral, apolitical environment, more likely to achieve acceptance than from other established bodies known to have special interests. After meetings in the USA, Europe, and at the RAeS Headquarters in London, a document was drafted and agreed unanimously at the RAeS in early 1992. This document covered proposed international standards for objective and subjective testing of flight simulators. The success of this process may be measured by the fact that the document has been accepted without alteration by the International Civil Aviation Organization (ICAO), and has greatly facilitated the writing of national regulatory rules on the subject. As an example, the European Joint Aviation Authorities (JAA), of which the UK is a Member, is in the process of incorporating the RAeS document into its Joint Aviation Requirements for Simulators (JARSIM). The IWG has greatly facilitated the building of trust between various national regulatory bodies, and a number of joint simulator evaluations have already taken place between the regulatory bodies in the UK, USA, Canada, Germany, and Australia. A number of re-evaluations of individual flight simulators have been accepted by these five authorities when completed to the RAeS standard by one authority. [26,27]

Chapter 2

2. The history of flight simulation.

The importance of training has been realized since the inception of manned flight. From the early days of gliding it was usual for "pilots" to sit in the glider, which was exposed to a strong facing wind and "feel" the controls by keeping the wings in a horizontal position. Thus, even before the glider flew, the pilot had some experience of the lateral controls.

2.1 Early days of flight simulation.

The fliers of the first powered aeroplanes learnt by proceeding through a graded sequence of exercises on real aircraft. After passenger flights, a student would perform taxiing, where a low powered machine is driven along the ground enabling rudder control to be practiced. He would then graduate to a higher powered machine and would first make short hops using elevator control. After longer hops he would eventually achieve flight. A variation of this method, known as the "penguin system", in which a reduced wing span, landborne aeroplane was used, was developed during World War I. In this machine the student pilot could learn the feel of the controls while proceeding along the ground. This method was used at the French Ecole de Combat with a cut-down Bleriot monoplane, but was considered as early as 1910.

Other early devices attempted to achieve the same effect, especially for the testing of new aircraft prototypes, by using aircraft moving at speed supported by balloons, overhead gantries or railway bogies. Related to these ideas were the first proposals for truly ground-based trainers which were, in effect, aircraft tethered to the ground, but capable of responding to aerodynamic forces. One such device was the Sanders Teacher.

The Teacher was constructed from components which could in fact be used to build an actual flying machine, and was really an aircraft mounted on a universal joint in an exposed position and facing into the prevailing wind. In this way it was able to respond in attitude to the aileron, elevator and rudder controls as would an actual aeroplane of the type. Unfortunately, as was the case with many of these early devices, it was not a success, probably because of the unreliability of the wind. A similar device was that constructed by Eardley Billing, the brother of Noel Pemberton Billing, at about the same time, and was available for use at Brooklands Aerodrome.

Also around this period was made one of the first truly synthetic flight training devices. It consisted of two half-sections of a barrel mounted and moved manually to represent the pitch and roll of an aeroplane. The pilot sat in the top section of this device and was required to line up a reference bar with the horizon.

2.2 World War I.

The need for the training of large numbers of pilots during World War I encouraged the development of the new discipline of aviation psychology and tests were introduced for aviator selection, the lead being taken in France and Italy. Many devices were invented to aid in the assessment of the aptitude of potential airmen. In 1915 such a machine was proposed for the measurement of reaction time in correcting disturbances; this consisted of a rocking fuselage fitted with controls and an electrical recording apparatus - the response of the student to tilting, manually produced by the examiner, being recorded. Further developments on this theme include the Ruggles Orientator, and the devices patented by Reid and Ocker. In all of the descriptions of these machines, it is stated that useful pilot training could also be undertaken with their use; this however, must have been of a very limited nature.

The Ruggles orientator, for example, consisted of a seat mounted within a gimbal ring assembly which enabled full rotation of the pupil in all three axes and in addition provided vertical movement. All motions were produced by electric motors controllable by the simulated sticks and rudder bars of the student and examiner. This device was stated to be useful for "developing and training the functions of the semi-circular canals and incidentally to provide such a machine for training aviators to accustom themselves to any possible position in which they may be moved by the action of an aeroplane while in flight", it must have been good fun too :-). A further optimistic claim was that the aviator could be blindfolded "so that the sense of direction may be sensitized without the assistance of the visual senses. In this way the aviator when in fog or intense darkness may be instinctively conscious of his position".

Aids were also produced for the training of other skills associated with aviation. Rolfe mentions German methods for the training of air gunners and observers, and the French are known to have used miniature painted landscapes for bomb aiming training.

The next step in the evolution of the flight trainer was the replacement of the human operator in Antoinette type machines with mechanical or electrical actuators linked to the trainer controls. The aim of these now automatic devices was to rotate the trainee pilot's fuselage into an attitude corresponding to that of the real aircraft in response to his control inputs. Provision was usually made for an instructor to introduce disturbances in attitude to simulate the effect of rough air and to present control problems to the student. An example of this technique is the family of devices described by Lender and Heidelberg, of France, in 1917. One of these consisted of a pivoted dummy fuselage with pitch, roll and yaw motions produced by compressed air motors and introduced, probably for the first time, variations of response and feel with simulated speed. Engine noise and a rudimentary visual presentation were also described.

An electrical version of this type of trainer was patented in the United States in 1929 by Buckley. This machine consisted of a small dummy fuselage mounted on a universal joint (which by now had become a common arrangement) with pitch and roll attitudes each produced by opposing motors proportionally controlled by stick movements while turning motion was provided by another motor actuated by controls on the rudder bar. Programmed disturbances could be introduced by means of a perforated tape arrangement which could also control the indications of dummy cockpit instruments; these were not, however, connected to the flying controls.

The most successful and well-known of this type of device was, the Link Trainer. Edwin Link gained his early engineering experience at his father's firm, the Link Piano and Organ Company of Binghamton, New York. The trainer was developed in the period 1927-1929 in the basement of the Link factory and made use of pneumatic mechanisms from the piano and organ business. The first trainer, touted as "an efficient aeronautical training aid - a novel, profitable amusement device" was described in a patent of 1930. Pitch, roll and yaw movements were initiated in the same manner as in its predecessors, but pneumatic bellows were used for actuation. An electrically driven suction pump mounted in the fixed base fed the various control valves operated by the stick and rudder, while another motor-driven device produced a repeated sequence of attitude disturbances. In common with other trainers of the time, the performance was adjusted by trial and error by the designer until the correct "feel" was obtained.

The first description of the trainer made no reference to instruments and the device was therefore primarily intended to demonstrate to students the effects of the controls on the attitude of the simulated aeroplane and to train them in their operation. As with other synthetic devices of this time, the simulated effects of the ailerons, elevators and rudder were independent; they did not represent a true reproduction of the aircraft's coordinated behavior. However, despite twenty years of development, simulation was not seen as a substitute for actual flight. The acceptance of simulated flight as a useful training aid had to wait for further developments in the science of flying.

2.3 Instrument Flight Training.

In the late 1920's the need was starting to be felt for the effective training of pilots in the skills of "blind" or instrument flying. Two methods were developed firstly the existing moving trainers, such as Link's, were fitted with dummy instruments and the means for their actuation, and secondly, non-movable devices were invented specifically for the task of instrument flight training.

Rougerie's patent of 1928 describes a simple trainer, fixed to the ground, consisting of a students seat facing an instrument panel and two sets of controls, one each for the student and instructor. The student's flight instruments are directly connected to the instructor's controls. The student, then, flies the trainer in response to commands from the instructor, who in turn modifies the instrument indications according to the students actions - the accuracy of the simulation depends entirely on the instructor. A further development of this concept can be seen in a development by W.E.P. Johnson in 1931, an instructor at the Central Flying School, Wittering, and one of the pioneers of instrument flying in Britain. He constructed his trainer from a written-off Avro 504 fuselage. In the simplest form of this invention an airspeed indicator, turn indicator, and bank indicator are directly operated by wires attached to the sticks and rudder bars of student and instructor. Further improvements included a throttle control affecting the airspeed indicator and integrating devices for the display of altitude and heading. It is interesting to note that a true simulation of accelerations due to aircraft motion was suggested. However, it seems that this idea was not to be taken seriously for more than twenty years.

Another early British instrument flight trainer is that described by Jenkins and Berlyn of Air Service Training Limited, Hamble, in their patent application of 1932. This ground-fixed apparatus used mechanisms similar to Johnson's for linking the instruments to the controls. Rotation of the magnetic compass was effected with a magnet, while transient deflections, were produced by causing a rotary movement of the compass damping fluid in response to pitch and throttle control changes.

The Link Trainers themselves were soon being fitted with instruments as standard equipment. Blind flying training was started by the Links at their flying school in the early 1930's and as the importance of this type of training was more fully appreciated, notably by the U.S. Army Air Corps, so the sales of Link Trainers increased. The newer Link Trainers were able to rotate through 360/Degrees which allowed a magnetic compass to be installed, while the various instruments were operated either mechanically or pneumatically. Altitude, for example, was represented by the pressure of air in a tank directly connected to an altimeter. Rudder/aileron interaction was provided in the more advanced trainers, as was a stall feature. The reproduction of aircraft behavior and dynamics was still produced in an empirical manner.

A further increase in the usefulness of the trainers was achieved with the attachment of a course plotter. This consisted of tortoise like device, on three wheels, which was self-propelled and steerable; the course of the simulated flight was traced on a chart by means of an inked wheel. By relating the position of the student's aircraft to marks on the chart, the instructor was able to manually control the transmission of simulated radio beacon signals to the trainer. In the 1930's the device was produced in various versions and was sold to many countries, including Japan, the USSR, France and Germany. The first Link Trainer to be sold to an airline was that delivered to American Airlines in 1937. The RAF also took delivery of their first Link in the same year. By the beginning of the Second World War, many of the major air forces were doing their basic instrument training on Links, or devices derived from them. The Link Trainers continued to be manufactured into the 1950's, their principle of operation remained the same.

Two of the first electrical flight trainers, both still based on empirical designs, were Dehmel's trainer and Travis' "Aerostructor". Dr. R.C. Dehmel, an engineer with the Bell Telephone Laboratories, became interested in flight training in 1938. His first development was an automatic signal controller for the generation of synthetic radio signals for a Link Trainer, thus eliminating the need for the attendant who manually operated signal volume controls during the training session. This was an important advance in instrument flight training in that it enabled a closer match with the behavior of actual navigational aids. Following this, Dehmel developed the "flight" portion of a trainer based on electrical circuits. This machine was never manufactured, but served as a starting point for future developments.

The Aerostructor, developed by A.E. Travis and his colleagues in 1939/ 40 also in the United States, was a fixed base, electrically operated trainer with a visual rather than an instrument presentation. The visual system was based on a loop of film and simulated the effects of heading, pitch and roll movement. The trainer was widely demonstrated in the U.S., but was never commercially produced. It was however, used in large numbers by the U.S. Navy in a modified form as the "Gunairstructor".

2.4 World War II.

At the start of the Second World War there was the requirement to train large numbers of people in the many individual and team skills involved in the operation of the various military aircraft. Basic pilot instruction was performed in part on Link Trainers both in the United States and Britain.

Developments in aircraft, such as variable pitch propellers, retractable undercarriage and higher speeds made training in cockpit drill essential. The mock-up fuselage was introduced as an aid to training in these procedures. One such device was the Hawarden Trainer, made from the center section of a Spitfire fuselage, which enabled training in the procedures of a complete operational flight. The Links too, were developed to the stage where the instrument layout and performance of specific aeroplanes were duplicated; the U.S. Army-Navy Trainer, Model 18 (ANT-18), for example, was designed for training in AT-6 and SNJ flying.

In 1939 the British requested Link to design a trainer which could be used to improve the celestial navigation capabilities of their crews who were ferrying "surplus" U.S. aircraft across the Atlantic. Such a trainer could also be used to improve bombing accuracy during night raids over Europe. Ed Link, together with the aerial navigation expert, P. Weems, worked out the design of a massive trainer suitable for use by an entire bomber crew, and housed in a 45 foot high silo-shaped building. This was the Celestial Navigation Trainer. The trainers incorporated a large-size fuselage similar to that of the conventional Link Trainer, but which could accommodate the pilot, navigator, and bomber. The pilot flew the trainer, which included all the facilities and instruments of the smaller conventional Link Trainer, while a bomb aimer's station provided the appropriate sight and targets over which the trainer flew. The navigator was provided with all the radio aids and, in addition, was provided with an elaborate celestial view from which he could take his appropriate astro sights. The stars, of which enough (12) were collimated, were fixed to a dome which was given a movement to correspond with the apparent motion of the stars with time and changes in bomber latitude and longitude.

The first Celestial Navigation Trainer was completed in 1941, and the RAF placed an order for sixty of them. Unfortunately, only a limited number of these trainers were installed in Britain, such as at the Link Trainer School at Elstree, and at a number of special RAF stations. The balance were returned to the U.S. Air Force under Reverse Lease Lend, with the exception of three sets of components which were subsequently used for navigational trainers. However, hundreds of these devices were installed and operated in the United States.

Throughout the war instructors on various RAF stations were contributing their ideas to training and numerous "home-made" devices were constructed due to the long delivery times and low priority given to the manufacture of training aids. An early development was the "instructional fuselage". Such a device would consist of fuselage of the desired type mounted on stands inside a hangar. It could then be used to train air crews in the drills that they have to carry out in the particular aircraft that they are being trained on. Services like, hydraulic, electrical, and pneumatic, and their recording instruments were made to work in a normal manner, so that the various drills carried out by the crew were realistic. Bomb-dropping procedure and abandon aircraft drills by parachute and dinghy were also carried out; the bombs being released into sand trays beneath the aircraft, (duds presumably). :-)

Of particular interest are the so-called Silloth Trainers, developed by Wing Commander Iles at RAF Silloth, south of Carlisle. The picture shows one of these trainers for a Halifax bomber. The Silloth Trainer was designed for the training of all members of the crew, and was primarily a type familiarization trainer for learning drills and the handling of malfunctions. As well as the basic flying behavior, all engine, electric and hydraulic systems were simulated. An instructor's panel was provided to enable monitoring of the crew and malfunction insertion. All computation was pneumatic, as in the Link Trainer. Silloth trainers were manufactured for 2 and 4 engined aircraft throughout the war; in mid-1945, 14 of these trainers were in existence or on order. Towards the end of the war a Wellington simulator was developed at RAF St. Athan, using contoured cams to generate the characteristics of the aircraft's flight and engines. This machine, however, did not supplant the Silloth Trainer, as all activity on these ceased at the end of the war.

In 1940 Rediffusion, whose manufacturing division later became Redifon, built a direction finding trainer for ground operators. This simulated the Bellini-Tosi goniometer DF equipment, whereby two such stations could take a fix on an aircraft transmission and pass the resulting information back to the pilot. A similar trainer was designed to train the operators of VHF stations to give fixes to fighter pilots. However, the most important member of this family of Redifon trainers was the C 100 DF and navigational trainer which was first produced in 1941 to train air crews in the skills of navigation using ground beacons.

The trainers were installed in five separate cubicles which housed the trainee pilot, navigator and radio operators, and enabled these crews under the control of an instructor, to carry out navigational exercises, plotting their track from the bearings set up by the instructor. This trainer was similar in principle to the other two Redifon trainers. Suitable decoupling was provided so that up to five receivers and goniometers could be operated from one set of transmitting goniometers enabling the instructor, at the cost of limited flexibility, to teach five crews simultaneously.

The transmitting goniometers were mounted on a chart at the position of the beacon stations so that the designated north/south stator coils were aligned with the meridian passing through the particular beacon. The DF receivers were standard RAF airborne units and it was thus possible to tune them in and operate them as would be done in real life. The complete receiving goniometer stators could be physically oriented by the "pilot" of each aircraft to correspond to the aircraft heading during the flight.

The equipment had provision for the superimposition of interference such as enemy jamming. Some installations were equipped with sound effects and epidiascopes so that pictures of target areas and other landmarks of importance could be projected in front of the trainer. These installations were known as Crew Procedures Trainers. Well over 100 of the C 100 navigational trainers were built and installed on RAF Bomber Command operational training units and navigational training stations throughout the country and in Canada at the Empire Air Training Stations until the end of the war, plus the small number of trainers installed on USAF stations in this country.

In late 1942 Rediffusion were instructed to install this equipment on the first of the American 8th Air Force's stations at Bovingdon, which was known as a crew replacement center. The American authorities quickly appreciated the benefits of this trainer and requested that it be made to operate with American equipment as installed in the B17 Flying Fortress. In 1943 Rediffusion developed for the American Air Force a Dead Reckoning Navigational Trainer to train up to ten navigators flying in formation. The production model of this trainer, the C500, utilized the C100 and provided hyperbolic Gee fixes with an existing static Gee trainer.

One of the best technological successes of the war was the part played by the Trainer Group at the Telecommunications Research Establishment (TRE) in the design of synthetic radar trainers. This group, under G.W.A. Dummer, developed trainers for all of the new radars developed during the war years. In addition to devices attached to Link Trainers, a novel flight simulator for training in AI (Aircraft Interception) was invented. This trainer, the Type 19, was a complete crew, fixed base, trainer for AI combat, which consists of four stages: following an interception course provided by a ground operator, guided by on-board radar, visual contact and the moment of firing. The type 19 provided training in the complete sequence by provision of positions for the pilot and AI operator, and instructors unit, computers for simulation of the attacking aircraft and the relative position of the "enemy", a visual projection unit and a course recorder. The flight simulation computer (known as the Type 8, Part II) was used in a number of TRE trainers, including mobile units whose function was to tour operational squadrons to train in the use of the latest versions of airborne radar. The visual projection system, designed by A.M. Uttley, was used in the larger AI training installations at RAF Operational Training Units. The image, displayed on a hemispherical cyclorama mounted in front of the pilot, consisted of a night sky and ground of controllable brightness with a tail silhouette of a bomber which moved correctly in bank, range, azimuth and elevation in response to relative movements of fighter and bomber. The first AI crew trainers went into service in 1941, while the first complete Type 19 trainer was installed in 1943. It has been estimated that the use of the TRE synthetic radar trainers saved £50,000,000 worth of aviation fuel alone.

In addition to the trainers mentioned, above many others were developed by adding extra features to the basic Link Trainer for such tasks as gunnery instruction. In Britain, the JVW Corporation Limited, formed to market and service Link Trainers, successfully produced a torpedo attack trainer for the Royal Navy, a tank trainer for the Army, and a night vision tester and glider station keeping device for the RAF. The epidiascope visual system for the Torpedo Attack Teacher was produced by Strand Electric, better known for stage lighting. Another simulator with a strong visual element was the Royal Aircraft Establishment's Fixed-Gun Trainer for fighter pilots, developed towards the end of the war, the needs for training in more specialized skills were met by the adoption of a multitude of purpose-built devices.

2.5 Electronic Flight Simulation.

A major advance in simulation during the war period was the use of the analogue computer to solve the equations of motion of the aircraft. The analogue computer, or differential analyzer, as it was then known, enabled simulation of the response of the vehicle to aerodynamic forces as opposed to an empirical duplication of their effects. It is difficult to make a complete separation of these two types of simulation as both may be present in the same device. However, certain devices clearly were true analogues and a number of these are the direct ancestors of the modern simulator.

The first known discussion of the computer method of flight simulation is that of Roeder in his 1929 German Patent Specification. Roeder treated the general problem of the instrument control of vehicles freely movable in space, such as airships, aeroplanes or submarines. His outlines of the requirements of a simulator for such a task could almost refer to a modern simulator. As an example of his technique he described the dynamic simulation of an airship height control system and a fluid-operated analogue computer suitable for this. No successful training devices are known to have resulted from this work. In 1939 Mueller, at MIT, described an electronic analogue computer for the faster-than-real-time simulation of aeroplane longitudinal dynamics. His interest was in aircraft design and the solution of the equations of motion, but as a postscript to his paper he mentioned the possibility of extending the time scale of the simulation and of including a man in the loop.

In 1941 an electronic simulator was designed and built at the TRE to serve as the "flying unit" for their AI radar trainers. This computer was based on the ideas of F.C. Williams, famous for his later work on digital computers, and used the velodyne, another TRE invention, for integration. The d.c. method of computing was used in the simulation of the simplified fighter aerodynamics. The first model of this computer (the Type 8 Part II) was constructed by Dynatron Radio Limited in 1941 and many were used throughout the war. Later, in 1945, a more advanced flying unit including feel forces was designed by A.M. Uttley for use in a new AI visual crew trainer. This, however, never saw service.

Also in Britain at about this time an electromechanical analogue computer for the simulation of aircraft longitudinal dynamics was proposed by G.M. Hellings, then working at the Ministry of Supply. Non-linear functions were generated with shaped cams, and it was sufficiently general to allow the characteristics of any chosen aircraft type to be represented. A mechanical version of this device, the Day Landing Trainer, was manufactured by General Aircraft Limited and used at the Empire Central Flying School. This trainer simulated longitudinal motions and had a pitch motion system with an endless belt, directly viewed visual model. Further development of the device was carried out after the war at Air Trainers Limited.

In 1941 Commander Luis de Florez, of the U.S. Navy, visited Britain and wrote his "Report on British Synthetic Training". This report was highly significant and influenced the establishing of the Special Devices Division of the Bureau of Aeronautics, the predecessor of the present Naval Training Equipment Center. Also in this year the Silloth Trainer concept was brought to the United States and one was erected at the Mohier Organ Plant at Hagerstown, Maryland. After evaluation it was decided to build an electrical version of the trainer as instability of adjustments due to humidity, temperature and ageing made the system unmanageable. The task of producing the new trainer was given to Bell Telephone Laboratories who produced an operational flight trainer for the Navy's PBM-3 aircraft. This device, completed in 1943, consisted of a replica of the PBM front fuselage and cockpit, complete with controls, instrumentation and all auxiliary equipment, together with an electronic computing device to solve the flight equations. The simulator had no motion system, visual system or variable control loading. A total of 32 of these electronic flight trainers for seven types of aeroplane were built by Bell and the Western Electric

Company during the war years. It has been stated that the PBM-3 was "probably the first operational flight trainer that attempted to simulate the aerodynamic characteristics of a specific aircraft" but this is debatable.

Since the development of his electrical instrument flight trainer Dr. Dehmel had gained experience in analogue computing techniques through his work on Bell's M-9 anti-aircraft gun directors. He applied this knowledge to the design of an instrument flight simulator based on an analogue computer. He was then able to interest the Curtiss Wright Corporation in the manufacture of these devices in 1943. After the development of a prototype trainer, the U.S. Air Force ordered two trainers from Curtiss Wright for the AT-6 aeroplane; this trainer was named the Z-1. These were followed by production examples designated the Z-2, -3 and -4.

After the war, competition from Curtiss-Wright stimulated Link to develop their own electronic simulators. Also at this time the value of the Link Trainer motion system was being called into question. The movements of the Link Trainer did not correctly simulate the forces experienced in flight, and in fact a ground-fixed trainer would more accurately locate the force vector in coordinated turning or level flight. Also, the axis of roll rotation was too far below the pilot to allow correct simulation of accelerations due to roll. It was argued that the modern pilot should not fly "by the seat of his pants", but by instruments. Ed Link disagreed and held the view that trainer motion was needed even if incorrect, since motion was present in flying. However, customer pressure caused Link to follow the trend to fixed base simulators. The company therefore developed their own electronic analogue computer which was used in their C-ll. jet trainer. A contract was awarded by the U.S. Air Force in 1949, and eventually over a thousand of these types were sold.

Meanwhile, Curtiss-Wright had contracted to develop a full simulator for the Boeing 377 Stratocruisers of Pan American Airways. The simulator was installed in 1948 and was the first full aircraft simulator to be owned by an airline. No motion or visual system were installed, but in all other respects the simulator duplicated the appearance and behavior of the Stratocruiser cockpit. The trainer was found especially useful for the practice of procedures involving the whole crew; emergency conditions could be readily introduced by the instructor on his fault insertion panel. Complete routes could be flown, as in real life, using the same navigational aids. This facility was used by other airlines, and in the words of a BOAC Captain, "From start to finish we had treated the whole exercise as if it were the real thing, and the cockpit was so complete in every detail that we soon forgot that we were not in an aeroplane" However, there were some reservations expressed about the lack of motion in a fixed-base simulation, which caused it to feel unnatural and could even cause control problems.

In 1947 an airlines company decided to buy Boeing 377 Stratocruisers, and knowing of Redifon's work on synthetic crew trainers, asked Mr. Adorian if a simulator could be built for this aircraft; the simulator was to be the same as that which Curtiss-Wright were building for Pan American. In order to comply with the BOAC requirement Redifon had to enter into an agreement with Curtiss-Wright and Dr. Dehmel and obtain clearance from the U.S. State Department. Work commenced on the construction of the simulator at Redifons Wandsworth works in January 1950. The computation was analogue, using 60Hz (U.S. mains frequency) signals and servo motors, contoured potentiometers and 400Hz synchros and magnesyns for aircraft instrument drives. The control loading unit used variable levers, servo controlled as a correctly computed function of air speed, with springs to produce the necessary forces. The unit took the form of a separate frame running the whole length of the fuselage and, as today, carried the flying controls, throttle pedestal and pilot's panels and seats. The simulator was finally accepted in October 1951 with the price to BOAC being £120,000.

Prior to the final acceptance of the Stratocruiser, BOAC gave another simulator order to Redifon, this time for a Comet I. This was to become the first jet transport simulator in the world, and was designed by A.E. Cutler. Whereas the first simulator's servos had been manufactured by Curtiss, the Comet servos and potentiometers were built by Redifon. This second simulator followed similar principles to that of the first, except that a carrier frequency of 50Hz was employed and no computed control loading was necessary as the aircraft used a fixed spring-loaded control system.

The first Curtiss-Wright, Redifon and Link simulators used the a.c. carrier method of analogue computer. Air Trainers Limited however, decided to use the d.c. method - a more demanding technology, but one capable of superior precision in simulation. Their first simulator using this technology was built for the RAF's Meteor aircraft. The d.c. method was later adopted by Link in the United States. Redifon, however, developed a system using a carrier frequency of 400Hz which was very successful. Also, at this time, mechanical analogue computers were constructed for use in the simpler "type trainers" by Air Trainers Limited.

2.6 Digital Simulators.

One of the restrictions in these early days was that aircraft manufacturers did not have much analytical information on the performance of their airframes and engines; the simulator manufacturers were therefore required to use ad hoc methods to achieve the desired aeroplane characteristics. This changed however, with the arrival of the large subsonic jet transport era when the aircraft manufacturers began to produce much more complete data and to perform more extensive flight development programs. Together with requirements for driving the motion and visual systems then being introduced and pressure from the operators to improve accuracy and thereby, they hoped, better transfer of training, significant increases in the amount of analogue computer hardware became necessary to satisfy them. At this point, the law of diminishing return began to operate, the cumulative errors caused by all the additional hardware exceeded the improved accuracy which should have resulted from the more extensive aircraft data, which demanded the extra hardware.

In addition, reliability began to fall in spite of improved hardware and design technology, or at best was only maintained by the efforts of maintenance teams. At that time, the required utilization was around 8-10 hours per day for five days per week. This was soon extended to six days per week, even then, the requirement of today, for a training utilization of virtually 24 hours per day for seven days a week could be foreseen. It thus became obvious that the demands for increased fidelity of simulation and reliability could no longer easily be met with analogue machines even with the use of the new solid state elements which had appeared. Around this time the second generation of digital computers, started to materialize, and were able to satisfy the speed and cost requirements of flight simulation. As a consequence, there was an almost total swing to digital simulation for all but the simplest trainers.

It was realized from the earliest days of programmable electronic digital computers that a potential application would be in real-time digital simulation. The advantages of digital computers, improved flexibility, repeatability and standardization, were approached by the U.S. Navy who initiated a research program at the University of Pennsylvania in 1950. The general purpose computers of the time could not be used directly for real-time flight simulation, due to their poor arithmetic and input-output capabilities. A special machine therefore, was designed at the University for their simulator, which was named UDOFT (Universal Digital Operational Flight Trainer). This computer was manufactured by the Sylvania Corporation and completed in 1960. The UDOFT project had demonstrated the feasibility of digital simulation and was mainly concerned with the solution of the aircraft dynamic equations. In the early 1960's Link developed a special purpose digital computer, the Link Mark I, designed for real-time simulation. This machine had three parallel processors for arithmetic, function generation, and radio station selection. In the late 1960's general purpose digital computers designed for process control applications were found to be suitable for simulation, with its large input - output requirement, and the use of special purpose machines declined. Today special purpose digital computers are only used in applications demanding very high speed processing, such as computer generated imagery.

Nearly all of the simulators produced up to the mid 1950's had no fuselage motion systems. This was justified by the statement that modern pilots did not fly "by the seat of their pants", but the fact remained that fixed-base simulators did not feel like aeroplanes to fly. It was found that a handling improvement could be made by empirical adjustment of the control loading and aircraft dynamics simulations which, in part compensated for the lack of motion. Proposals were made by the manufacturers for motion systems, but it was not until the late 1950's that the airlines decided to purchase them.

In 1958, Redifon received a contract from BOAC for the production of a pitch motion system as part of a Comet IV simulator. More complex motion systems were designed capable of producing motions in two and three degrees of freedom, and with the introduction of wide-bodied transport aircraft, such as the 747, a lateral acceleration was required which led to the introduction of four and six degrees of freedom systems. Six degree of freedom motion systems are now the most common. The perception of motion and its effect on training is one of the less understood aspects of simulation and research is still active in this area.

Systems for producing the extra-cockpit visual scene have been proposed and constructed for almost as long as flight simulators themselves. However, realistic and flexible visual attachments are a fairly recent development. Due to the large number of visual systems which have been invented, only some of the more successful ones can be mentioned here.

The point-light source projection, or shadow graph, method enjoyed popularity in the 1950's, especially for helicopter simulators. A series of simulators using this method of visual display were produced by Giravions Dorand in France including an ab initio hovering trainer produced by Shorts of Belfast in 1955. Simulators on this pattern were also built in the United States, but the shortcomings of the shadow graph system seems to have limited the success of the concept. The first visual systems achieving widespread use on civil aviation simulators were based on the scale model and television camera method, although methods based on film and anamorphic optical systems have also met with success for more restricted applications. Serious development of closed-circuit television visual systems began in the mid 1950's with monochrome systems being produced by Curtiss-Wright, Link (then the Link division of General Precision) and General Precision Systems (formerly Air Trainers and Air Trainers Link Limited). The first color system was produced by Redifon in 1962. Television based visual systems have under gone a steady development since then, with a large part of the effort being devoted to improved methods of image display.

The first computer image generation systems for simulation were produced by the General Electric Company (USA) for the space program. Early versions of these systems produced a patterned "ground plane" image, while later systems were able to generate images of three-dimensional objects. Progress in this technology has been rapid and closely linked to developments in digital computer hardware technology. Current systems available from major simulator manufacturers are able to produce full color images with scene contents of several thousand polygons and point-light sources. A parallel development has taken place in night-only computer image generation systems; these use the calligraphic or stroke-writing, rather than the raster scan method of display, which enables a superior reproduction of light points. The first of these systems was produced by the McDonnell-Douglas Electronics Corporation in 1971 and called Vital II. Current systems, can produce images of night, dusk, and daylight, using resolutions of around 800,000 pixels, over 1000 surfaces, over 3000 light points all per channel, of which there may be 3 or 5, on a typical simulator, they can employ texture maps, and photographic images of real ground details, all manipulated in real time, at a frame rate of 50Hz.

Much effort has been devoted to improving the instructional facilities in the simulator. The use of high resolution touch screens for instructor control, and substantial increases in the number of malfunctions and radio stations which can be offered, there are also facilities for exercise recording and playback, pilot performance recording and evaluation, separate pilot and flight engineer training in the same exercise and automated training. We have now reached a point in commercial flying training, where all conversion and recurrent training can be conducted in a simulator, so that a pilot of one aircraft type, can be cross trained to another, without ever actually having flown the real target aircraft, until he or she is on board, carrying fare paying passengers. [39] For additional information, the reader may refer to [1,2,7,10,13,17,25,32,33,36]

Chapter 3

3. Description of simulation complex.

This chapter describes the various systems and facilities that are used for the numerous real-time simulation projects.

3.1 Advanced Real-Time Simulation System (ARTSS).

The following is a brief description of each major component of this system (NASA system). [30,31]

3.1.1 Mainframe Computers.

The mainframe computers are used to provide a mathematical solution of an aircraft simulation model. The computer complex has two mainframe computers allocated for simulation, a HP/CONVEX C3840 and a HP/CONVEX C3830. Both machines have multiple central processors available for real-time simulation. The C3840 has four CPU's of which three are available for real-time. The additional CPU is used to run the UNIX operating system. The C3830 has three CPU's, of which two can be used for real-time and one is reserved for UNIX. Multiple CPU's allow multiple real-time simulation programs to be run concurrently. Using the shared memory capability of the HP/CONVEX computers, a single simulation may use as many as three CPU's on the C3840 and two CPU's on the C3830.

3.1.2 Computer-Aided Measurement and Control (CAMAC) Highway.

A CAMAC (Institute of Electrical and Electronics Engineers (IEEE) standard) highway is a high-speed digital network that links the mainframe computers with the simulator site hardware. Each highway is made up of several devices - the Block Transfer Serial Highway Driver (BTSHD), the switch network, the fiber-optic highways, and the site crate that varies with the type of simulator site. Each of these devices will be discussed.

The ARTSS contains multiple highways that can be used to support several totally independent simulations running concurrently.

3.1.2.1 Block Transfer Serial Highway Driver (BTSHD).

This unit provides the link between the mainframe computer and the CAMAC serial highway. The BTSHD is the highway master and directs all communications between the mainframe computer and the simulator site crate modules. The transfer rate of the CAMAC serial highway is 24 million bits per second.

3.1.2.2 Switch Network.

The purpose of the switch network is to provide complete connectivity between the simulation applications program on the mainframe computer and the various simulation sites required by the simulation. A simulation site is an allocable collection of equipment, such as a simulation cockpit, a control console, or a graphics channel. Upon request, any sensible arrangement of available simulation sites can be combined into a local computer network in support of a simulation. A network is configured for a given simulation during the initialization phase after a highway has been assigned by the scheduling software. The applications job requests the sites to be configured and if these sites are available, the switch system will configure the requested network without disturbing other running simulations. The switch matrix performs the actual highway/site switching. The switch matrix has the capability to connect any of 28 simulator sites to any of 6 highways. The current switch capability will allow up to 36 sites and 12 highways.

3.1.2.3 Fiber-Optic Highway.

At the switch system the electrical signals are converted to light signals by a fiber-optic transmitter/receiver, called a Fiber-Optic Universal Port Adapter (FOUPA), for transmission to sites that are located at distances of up to 1 mile.

The fiber-optic highway consists of two components: a pair (one at the switch and one at the simulator site) of FOUPA modules to convert signals from electrical to light and vice-versa, and a transmission line made up of light conducting fibers. Each FOUPA contains both a transmitter that converts the 8-bit wide plus clock byte serial electrical signal to a 1-bit serial (50 megahertz (MHZ)) light signal that is transmitted through the fiber-optic cable and a receiver that receives the light signal from the cable and converts this signal to a 8-bit wide plus clock byte serial electrical signal.

3.1.2.4 Site Crate (Simulator Interface).

A CAMAC crate is a printed circuit card cage with power supply that has 25 slots for cards. A backplane in the cage is called the dataway and provides interconnection between cards in the cage. Each simulation site has at least one site crate.

3.1.2.5 Block Transfer Serial Crate Controller (BTSCC).

The final element in the CAMAC highway is the BTSCC located in the site crate. Each crate at the site has a BTSCC. The FOUPA transmits the 8-bit wide byte serial data to the BTSCC of the first crate of the simulator site and, for those sites with multiple crates, receives 8-bit wide byte serial data from the BTSCC of the last crate in the site. The BTSCC manipulates and conditions the data from the FOUPA to make it compatible to communicate to the crate dataway; vice-versa, data from the crate dataway is manipulated and conditioned to make it compatible with the 8-bit byte serial data required by the FOUPA for transmitting on the CAMAC highway.

The BTSCC requires other modules located in the site crates to make the system work as designed:

- For those sites with a minicomputer, the minimum additional interface modules required are a Minicomputer Interface Module (MIM) and a Look At Me (LAM) Encoder (module that produces signals similar to interrupts).
- For the conventional simulator sites that require signal conversion modules for their interface, the minimum additional modules required are a List Sequencer Module (LSM) (for addressing, see below), a SiteClock Interface Unit (SCIU) (see below), the signal conversion modules, and for those sites that have asynchronous devices such as the MIM, a LAM Encoder is required.

3.1.3 Clock System.

The purpose of the clock system is to synchronize simulations to the real-time clock and to other simulations. The clock system is composed of a central unit, a SCIU, and a fiber-optic distribution network:

- The central unit is the central timing source for all simulation sites. It employs an accurate temperature controlled oscillator from which it derives the timing signals that are sent to the sites.
- The SCIU is a CAMAC module that resides in one of the simulator site crates. The SCIU has a fiber-optic receiver and it decouples the two timing signals sent by the central unit. The timer board is a Versa Module Europcard (VME) board that resides in a VMEbus attached to the simulation computer or other computing device. The timer board decouples the two timing signals and provides programmable timers.
- The Fiber-Optic Distribution Network. At the central clock unit, a distribution chassis contains multiple fiber-optic transmitters which are arranged in a "star" network. One fiber - optic transmitter is required for each site connected to the ARTSS.

3.1.4 Simulator Sites with Minicomputers.

Two categories of modules make-up the interface for this type site:

- The Highway Interface Modules. These consist of the FOUPA and the BTSCC. These modules provide the data link between the CAMAC highway and the site crate dataway.
- The MIM. Simply stated, this module provides the data link between the crate dataway and the minicomputer. This module contains a two segment, dual-ported memory. One segment is for data written from the crate dataway and read by the

minicomputer; the other segment is for the data written from the minicomputer and read by the crate dataway. Typically, sites with minicomputers are interfaced through a single CAMAC crate.

3.1.5 Simulator Sites with Signal Conversion Interface.

These sites normally require multiple (currently up to four) crates to house all required modules. Four categories of modules make-up this type site:

- Highway Interface Modules. Three types of modules make-up this category of equipment:

1. FOUPA which was described previously. Regardless of the number of crates are required in a site interface, only one FOUPA is required at each site.
2. BTSCC which was described earlier. A BTSCC is required at each crate that makes up the site interface. The BTSCC must occupy slots numbered 24 and 25 of the crate.
3. LSM which was mentioned earlier. The LSM is used during real-time operation. It contains a memory that is divided into two segments, one containing CAMAC NAF (module slot number, module address, module function code such as read and write) commands for data input modules, the other a similar set of commands for data output modules. The memory for the two lists is written at system start-up time. During real-time operation the data is transmitted to and from the mainframe computer in blocks of contiguous data. The LSM, under control of the BTSCC, sequences through the proper list of commands and scatters or collects data to/from the proper modules. Each crate of the simulator interface must have a LSM.

Several simulator sites contain MIM or other similar devices that require asynchronous data transfer. To accommodate these devices, a LAM Encoder is required at each crate containing an asynchronous module. This module causes the BTSCC to issue a demand message (similar to an interrupt) to the mainframe computer indicating that one of the asynchronous modules in the crate needs attention. This is as close as the ARTSS gets to an interrupt.

- SCIU. This module, as described earlier, generates the timing signals that are required for synchronized real-time operation.
- Signal Input/Output Conversion Modules. Currently there are five module types that make-up this category of site interface equipment:

1. Analog-to-Digital Conversion (ADC) Module. This module, as the name implies, converts analog signals (+10V) from the simulator hardware into digital data for transmission to the mainframe computer. Each ADC Module contains six converter channels. Each ADC channel is a 16-bit (sign bit plus 15 data bits) device. The data is packed onto the crate dataway using two 24-bit CAMAC words to pack three 16-bit ADC channels. The ADC Modules are built by Kinetic Systems Corporation (KSC), Model 3595-ElA.

2. Digital-to-Analog Conversion (DAC) Module. This module converts a 16-bit (sign plus 15 data bits) into an analog output (+ 10V). Each DAC Module contains six converter channels. The data comes from the mainframe computers packed as three 16-bit DAC channels into two 24-bit CAMAC words. The DAC Module is KSC Model 3195-ElA.

3. Discrete Input (DI) Module. This module converts 48-bits of discrete signal information from the simulator into digital data for transmission to the mainframe computers. Two 24-bit CAMAC words are required to pack the 48 data bits from this module. The DI Module is KSC Model 3495-ElA.

4. Discrete Output (DO) Module. This module converts one 24-bit CAMAC word into 24 bits of discrete data for use by the simulator. Two types of DO Modules are used:
   - KSC Model 3095-ElA, populated with reed relays; and KSC
   - Model 3095-ElB, populated with optical isolators.

5. Digital-to-Synchro Converter (DSC) Module. This module converts digital information into 26 volt, 400 cycle synchro transmitter compatible data for driving synchro devices at the simulator site. Each DSC Module contains three synchro channels. The data comes from the mainframe computer packed as three 16-bit DSC channels into two 24-bit CAMAC words. Each synchro channel receives 16-bit digital information as input and converts this to + 4 arc-minute accurate synchro data. The DSC Module is KSC Model 3395-ElA.

- The final category of modules used at the site crates are those modules and external equipment needed to make-up the local processor. The local processor is currently used in both on-line (real-time) and off-line (nonreal-time) modes. In on-line mode the local processor is used to send and receive serial (RS-232C) data in real-time. In off-line mode the local processor is used for diagnostic testing of crate modules and for pre-run checks of the simulator hardware.

The local processors are currently being upgraded. The new local processors will perform the following functions: interface to the CAMAC highway through a MIM card, provide serial communications with at least eight individually configurable RS-232C lines, and allow ETHERNET communications. This new local processor is an Intel 486 based computer running a real-time UNIX operating system derivative named Lynx. [11,35]

3.1.6 Silicon Graphics Incorporated (SGI) Computers.

A few companies are currently implementing the use of SGI computers to provide the mathematical solution of simulation models. Two ONYX series computers with eight R4400 CPU's each are available. The operating system on these computers will support only one simulation per computer. The CPU's provide a significant performance increase over the HP/CONVEX computers. In addition to providing simulation model computing, these computers offer a significant graphics capability.

These computers are connected to the ARTSS through the CAMAC network configuration switch and have full connectivity with all the simulation sites on the CAMAC network.

3.1.7 Shared Common RAM Network (SCRAMNet) Real Time Network.

The use of SCRAMNet is to provide an additional real-time networking capability. SCRAMNet is a real-time communication network, based on a replicated shared memory concept. Each computer or device on the network has access to its own local copy of the SCRAMNet shared memory which is updated over a high-speed, serial ring network. It is optimized for the high-speed transfer of data among multiple, real-time computers or devices attached to the network.

3.2 Special Purpose Systems and Facilities.

This section describes the special purpose systems and facilities that are available to each simulation program.

3.2.1 Instrumentation Graphics Generators.

Two classes of graphics generators are currently used to generate cockpit instrumentation displays:

The Calligraphic Raster Display System (CRDS) is one type of graphics system currently being used to generate real-time graphics for cockpit instrumentation displays. The CRDS consists of three Terabit Computer Engineering Eagle 1000 units which are integrated into the ARTSS. These units generate the necessary color graphics for the various Cathode Ray Tube (CRT) displays located in each of the simulators.

The Eagle 1000 can be used as a standalone workstation with multi-user capability for development work. The Eagle 1000 is interfaced through the CAMAC highway to the supercomputers where it serves as a real-time interactive terminal. Each unit can support only one real-time simulation program at a time. The Eagle 1000 has a UNIX-based, C programmable computing and development environment.

The Eagle 1000 units are equipped with four independent calligraphic and/or hardware anti-aliased Raster Mixer (RMIX) image generation channels. Two units, which are used as production machines for nonsecure applications, have one RMIX and three calligraphics channels; the RMIX channel has an added capability of accepting an external raster source for mixing. The remaining unit, which is used for secure applications, has four calligraphic channels. Each calligraphic channel can drive four CRT's and each raster channel can drive one CRT. Test results have shown that a simulation program can successfully drive up to eight independent and highly complex calligraphic displays (two per channel) in the real-time environment.

The second type of graphics system is the SGI-ONYX raster graphics generator. Two SGI-ONYX raster graphics generators are used to generate raster

type cockpit instrumentation displays. Each of these machines are equipped with Reality2 (RE2) graphics engines with three graphics pipes.
These machines will be upgraded to Reality3 (RE3) graphics engines in the near future.

The SGI-ONYX graphics generators can be used as a standalone workstation with multi-user capability for development work. The SGI-ONYX graphics generators are interfaced through the CAMAC highway to the supercomputers where they serve as real-time interactive terminals. Each unit can support only one real-time simulation program at a time. The SGI-ONYX has a UNIX-based, C, or C++ programmable computing and development environment.

Each SGI-ONYX RE2 is equipped with three graphics pipes, each of which is capable of generating multiple displays at different display resolutions.

3.2.2 Out-the-Window Scene Generation.

The LaRC FSF currently has three Computer-Generated Image (CGI) systems for generating out-the-window scenes for simulator cockpits; one CT6 and two ESIG-3000GT units. These systems are described below.

The first CGI system consists of an Evans and Sutherland special purpose image generating mainframe (CT6) connected to a general purpose computer (Gould 32/6781) for communications and control.

This system consists of four raster-only output channels with 500,000 pixels per channel. This CGI is capable of providing two independent eyepoints (i.e., views of a data base). Each eyepoint is capable of operating in one of two data bases, the dome data base or the Denver data base. These eyepoints can be used in independent simulations in the same data base, independent simulations in different data bases, or collocated in the same data base to provide all four channels to the same simulation.

The dome data base is primarily for use with the Differential Maneuvering Simulator (DMS) although it can be used with any of the other simulators. The DMS consists of two 40-foot diameter projection spheres onto which the CGI projects an image. This data base is a 400 nautical mile (nm) by 400 nm gaming area complete with generic terrain (farmland, mountains, and rolling hills) and two airports. One airport is used for research while the second is a specially designed area for demonstration purposes. Distortion of the image, which is inherent in a dome projection, is corrected by the use of a technique known as Non-Linear Image Mapping (NLIM). This technique corrects the distortion so that all aspects of the image appear to be correct when viewed by the pilot at the center of the dome. The target models that may be projected in the dome data base are the F-14 (three wing positions), F-16, F-18, X-29, and MIG-20. However, due to the resolution in the dome, the models are good only for formation flying range (less than 300 feet).

The Denver data base is centered around the Denver Stapleton Airport and modeled with Defense Mapping Agency (DMA) data. This airport is modeled in its entirety including all runways, taxiway, terminal buildings, strobe lights, beacon lights, runway lights, taxiway lights, approach lights, and Vertical Approach Situation Indicators (VASI). Surrounding the airport are a few buildings, a water tower, and the city of Denver. The target models that may be displayed are the B-707, B-727, and DC-10. Any three of these models can be active in the scene at any one time with control from another piloted simulator or a simulation facility:

Both data bases have the following capabilities:

- Variable ambient visibility
- Variable sun intensity

- Cloud cover
- Ground fog and haze
- Texture
- Lights
- Landing light lobes
- Rates of motion
- Weather effects
- Height above terrain
- Collision detection
- Line of sight ranging
- Occultation

The second CGI system, the Advanced Computer-Generated Image (ACGI) system is a high-performance graphics system designed to provide an out-the-window scene for piloted simulations. The system consists of two Evans & Sutherland ESIG-3000GT Image Generator Systems (IGS's). Each IGS provides a single ownership with multiple display channels, IGS-0 is a five display channel machine and IGS-1 is a three display channel machine.

Each IGS has multiple on-line data bases available to provide a realistic view of selected geographic areas. Currently available are the Denver International Airport, Boston Logan International Airport, and the Shuttle Mission Training Facility (SMTF) data bases.

The Denver International data base provides generic terrain typical of the Denver region for a gaming area of approximately 200 nm by 200 nm. An area of 100 nm by 100 nm surrounding the airfield contains geospecific terrain and features.

The Boston Logan data base provides generic terrain typical of the Boston region for a gaming area of approximately 75 nm by 75 nm. An area of 10 nm by 10 nm surrounding the airfield contains geospecific terrain and features.

Each of these data bases provide the following commercial transport models: DC-10, B-727, B-737, B-747, B-747-400, B-757, B-767, B-777, MD-11, MD-88, and a light twin turboprop typical of a commuter type airplane. Also available in each of these data bases, are moving models of ground equipment which can be placed around the airfield to create a more realistic terminal environment.

The SMTF data base is a integrated system of an earth orbital data base that contains the Space Station Freedom, assorted satellites, Shuttle payload bay with Remote Manipulator System (RMS) arm, and assorted payloads and accurate earth and star models together with multiple airfield data bases of Shuttle landing sites. This integrated system of data bases provides smooth transition to and from the earth orbital data base without any abnormal visual effects and without intervention by the IGS operator. The following is a list of landing sites:

- Edwards Air Force Base, California
- Kennedy Space Center, Florida
- White Sands Missile Range, New Mexico
- Zaragoza, Spain
- Ben Guerir, Morocco
- Banjul (Yundum International)
- Moron, Spain
- Moses Lake (Grant Co. Washington)
- Bermuda NAS, Bermuda
- Hickman Air Force Base, Hawaii
- Dakar, Senegal
- Eielson Air Force Base, Alaska

- Kadena Air Force Base, Japan
- Vandenburg Air Force Base, California
- Hao (French owned atoll in South Pacific)

The ACGI data base's provide realistic scene effects such as day, dusk, night, continuous time-of-day progression, and various weather effects. The following weather effects are modeled:

- Runway Visual Range adjustable from 0 to 500 mile in increments of .03 percent
- Ground fog extending from the ground to a controllable ceiling altitude
- Two continuous cloud layers with control of cloud tops and cloud bottoms
- Storm cells with three levels of severity
- Random lightening flashes and bolts positioned relative to a storm center

Other displays effects supported on the ACGI:

- Model animation to represent such things as gear and flap action
- Landing light glare and lobes
- Anti-collision light glare in fog and clouds
- Horizon glow adjustable in intensity and direction
- Sensor simulation such as FLIR/thermal, Night Visual Gargles (NVG) and/or low light level electro-optical

- Symbology applied to a single channel for Heads-Up Display (HUD) generation

A Scene Modeling System (SMS) is available for off-line development of new data bases and to perform modifications to existing data bases.

3.2.3 Video Distribution System.

Several video distribution subsystems are used to distribute the various source videos to the different simulators:

CRDS Video - these sources are used primarily to generate heads down, calligraphic type video displays at the simulator. The distribution system for the calligraphic and raster video signals from the CRDS consists of cable patchpanels to distribute the video from the CRDS source to the simulator cable trunks. Video amplifiers are used at both ends of each simulator trunk to allow driving the long coaxial cables with good signal fidelity. Two video distribution subsystems are provided: one is for secure operations; and one for nonsecure operations. The two subsystems can operate independently or connected via a removable patchpanel located in the wall of the secure computing facility and interconnecting trunks.

SGI-ONYX Video - These video sources are used to generate raster heads down displays for the simulators. The raster video from the SGI-ONYX graphics generators is first buffered with high-bandwidth video distribution amplifiers, then distributed to simulator trunks via video source switches. Trunks to the simulator displays are of two types: Coaxial cable with buffer amplifiers at the simulator end; or fiber-optic video system consisting of transmitter units at the source end, fiber-optic cable, and receiver units at the simulator end.

CGI Video - The CGI video is used to generate out-the-window displays at the simulators. Two types of video distribution are required:

- Simulator Displays with Calligraphic Lights: These signals are sent to the simulator displays either direct via coaxial cable (<150 ft.); or via fiber-optic video link. A calligraphic video switch at the source is used to direct the video signals to the proper simulator.

- Raster Simulator Displays - The raster video signals are sent to the simulator displays via a raster video distribution system located in the Simulation Video Lab. The distribution system is made up of high-bandwidth video distribution amplifiers, video switches, and coaxial cable trunking to the simulator displays.

3.2.4 Intercom System.

The simulation intercom system provides voice communications for all simulation programs for the simulation complex. This system is a satellite subsystem of the Langley Telephone System (LaTS). The simulation intercom system uses the LaTS central switching subsystem to provide up to 10 simultaneous conferences, each of which can have up to 12 simulation intercom stations connected. The stations are composed of program operator control stations, simulator cockpit stations, graphics generator stations, monitor stations, etc. The normal station equipment used for voice communications at the various stations are headsets, handsets, microphones, and speakers. Each conference is preprogrammed to connect the appropriate stations to be used with a simulation program. At the start of the simulation session, the program operator initializes the conference from an intercom control console; by selecting the simulation program, each station is dialed and connected to the conference.

A standalone intercom subsystem with independent switching that can be totally isolated from other parts of the simulation intercom system is used for secure simulation programs. This subsystem provides six conferences with up to four stations on each conference. For operation in secure mode, the console operator uses the console intercom phone to dial in the stations being used for the simulation program. During nonsecure operations, those stations in the secure computing area (console 4, CRDS 3) are connected via through the wall signal access panel to the nonsecure simulation intercom system.

3.2.5 Mission Oriented Terminal Area Simulation (MOTAS) Facility.

The MOTAS facility is an advanced simulation capability that provides an environment in which flight management and flight operations research studies can be conducted with a high degree of realism.

The major elements are an airport terminal area environment model, several aircraft simulators, and a realistic air-ground communications network. The airport terminal area represents the Denver Stapleton International Airport and surrounding area with either an advanced automated Air Traffic Control (ATC) system or a present-day vectoring ATC system using air traffic controllers.

The MOTAS facility combines the use of several aircraft simulators and pseudo pilot stations to simulate aircraft in the airport terminal area. The facility is presently operational with various simulators. These aircraft simulators allow full crews to fly realistic missions in the airport terminal area. The remaining aircraft flying in the airport terminal area are flown through the use of the pseudo pilot stations. The operator of these stations can control five to eight aircraft at a time by entering commands to change airspeed, altitude, and direction. The final major components of the facility are the air traffic controller stations, which are presently configured to display and control the two arrival sectors, the final approach sector, and the tower and/or departure sectors. [8,21,23,27] For additional information, the reader may refer to [3,4,6,9,14,37]

3.3 Simulator Facilities.

This section describes a few simulators and some example research applications for these simulators.

3.3.1 Differential Maneuvering Simulator (DMS).

The DMS provides a means of simulating two piloted aircraft operating in a differential mode (the pilots maneuver relative to each other) with a realistic cockpit environment and a wide-angle external visual scene for each of the two pilots.

The DMS consists of two 40-foot-diameter projection spheres. Each sphere contains an identical fixed-based cockpit and projection system. Each projection system consists of two terrain projectors to provide a realistic terrain scene, a target image generator and projector, a laser target projector, and an area-of-interest projector which project onto the sphere. The terrain scene, driven by a CGI system, provides visual reference in all six-degrees-of-freedom allowing unrestricted aircraft motions.

Each cockpit provides color graphics displays; standard fighter controls such as stick, pedals, and throttles; simulated engine sounds and wind noise; and cockpit vibration which add realism. In addition, g-suit and g-seat pressurization systems are used to simulate forces of gravity that a pilot experiences while performing maneuvers during flight.

This dual simulator can be tied to a third dome (the General Purpose Simulator (GPS)) and thus provides three aircraft interaction when required.

Research applications include studies of advanced flight control laws, helmet-mounted display concepts, and performance evaluation for new aircraft design concepts for development programs.

3.3.2 General Aviation Simulator (GAS).

The GAS consists of a general-aviation aircraft cockpit mounted on a three-degree-of-freedom motion platform. The cockpit is a reproduction of a twin-engine propeller-driven general-aviation aircraft with a full complement of instruments, controls, and switches, including radio navigation equipment.

Programmable control force feel is provided by a "through-the-panel" two-axis controller that can be removed and replaced with a two-axis side-stick controller that can be mounted in the pilot's left-hand, center, or right-hand position. A variable-force-feel system is also provided for the rudder pedals. The pilot's instrument panel can be configured with various combinations of CRT displays and conventional instruments to represent aircraft such as Cessna 172, Cherokee 180, and Cessna 402. A collimated-image visual system provides a 60 degrees Field-of-View (FOV) out-the-window color display. The simulator is flown in real-time with a HP/CONVEX C3840 supercomputer to simulate aircraft dynamics.

Research applications have included studies to evaluate the impact of various levels of data link capability on General Aviation (GA) SPIFR operations, and an investigation of flight control problems encountered in recovering a twin-engine GA aircraft to normal flight after one engine fails.

3.3.3 General Purpose Simulator (GPS).

The GPS is a single seat fixed-base fighter simulator. The system consists of a cockpit inside a 20-foot diameter projection sphere. The cockpit presents to the pilot standard fighter instrumentation, single or dual throttles, programmable control forces for pitch and roll, and a spring-loaded rudder system. The instrument panel has two 14-inch CRT displays. The standard pitch and roll controls can be replaced with a spring-loaded hand controller. The dome projection system consists of a horizon line projector and two laser target projectors representing other aircraft typically being flown by pilots in the DMS. A HUD is available.

3.3.4 High-Speed Research/Part Task Simulator (HSR/PTS).

The HSR/PTS is a research facility designed to meet the requirements of the flight deck element of the HSR program that are not met in existing or planned facilities. The HSR/PTS must be flexible to allow for maturity in the knowledge and assumptions about the High-Speed Civil Transport (HSCT), and generic enough to serve future research programs of the U.S. aerospace research community. The HSR/PTS is a full mission, full workload, two-crew member cockpit. The simulator supports a total of nine cockpit displays. Four are located on the main instrument panel, three on the overhead panel, and two on the center control stand. Each cockpit display consists of a Thin Film Transistor Liquid Crystal Display (TFT-LCD), a touchscreen, and an analog video Red/Green/Blue (RGB) interface compatible with Silicon Graphics Computers. The TFT-LCD presently used is a SHARP 13.8-inch wide viewing angle panel. The viewing angle is 140 degrees horizontal and 110 degrees vertical. The panel has a resolution of 1024 by 768 pixels and displays 264,144 colors. Extensive use of low cost TFT-LCD panels and touchscreens allow the HSR/PTS to represent graphically various types of transport aircraft and makes the cockpit highly reconfigurable.

Each pilot has a collimated out-the-window visual display on the side window and an uncollimated Forward Vision System (FVS) display on the front window. The FVS consists of two 27-inch high-resolution monitors in a portrait configuration. Both systems provide a combined FOV for each pilot of 104.5 degrees horizontal by 34 degrees vertical for the collimated system and 45 degrees vertical for the FVS. The collimated and FVS visual systems are compatible with raster video from the ACGI and the Silicon Graphics systems. The FVS will support a graphical HUD by mixing SGI HUD information with ACGI background video. As a second option to generate a HUD, a CRDS raster-mix video signal may be used.

Two wheel/columns, and two sidestick control inceptors are supported via a hydraulic digital control loader. The digital control loader provides a user friendly interface that allows an easy and quick way to change inceptor position and feel characteristics. Only one type of control inceptor can be connected at a time. Each pilot's control inceptor can operate independently or electronically coupled. Furthermore, the inceptor can be back-driven from a host computer. In addition to supporting wheel/columns and sidesticks, the simulator was structurally designed to accommodate a center stick. Spring loaded rudder pedals are provided with an integral toe brake system. Cockpit sounds (engines, RPM, airspeed, etc.), caution and warnings cues, and pre-recorded voice messages are generated using a Musical Instrument Digital Interface (MIDI) sound simulator.

Some of the research studies scheduled for the HSR/PTS include: crew/autoflight system integration, piloted integrated flight/propulsion control, management of abnormal situations, tactical flight path management, crew interaction with automation, and HSR Reference H Flexible Flying qualities.

The HSR/PTS is one of four simulators designed for use with the Cockpit Motion Facility.

3.3.5 Research Flight Deck (RFD) Simulator.

The RFD is a full-mission simulator and is representative of an advanced subsonic transport. The RFD simulator is a ground-based version of the research flight deck that is being designed and proposed for installation in the passenger compartment of the NASA-owned Boeing 757 airplane. The cockpit layout is based on the best characteristics found in several of today's newest transport aircraft. The RFD has an "all-glass" instrument panel and presents information to the crew via eight Aeronautical Radio, Incorporated (ARINC) D size electronic displays. Three displays are located in front of each crew member and convey flight, guidance and aircraft systems information. The two center displays (one located in the Center Control Stand) display EICAS information. The glare shield houses a researcher designed Mode Control Panel based an MD-11. The out-the-window information is displayed on a SEOS Panorama Display System. The display system will provide a collimated 200-degree horizontal by 40-degree vertical FOV to both the pilot and co-pilot of the simulated aircraft. This display will be tilted by 3-degrees around the pilot and co-pilot eyepoint to provide a -23/+17 degree vertical FOV. The Panorama uses advanced raster/calligraphic projectors to improve the realism of airport lighting displays.

Flight control inputs are provided via two sidestick controllers and two rudder pedal systems. They are both hydraulic digital control loader systems. The digital control loader system provides a user friendly interface that allows an easy and quick way to change inceptor position and feel characteristics. Each control inceptor can operate independently or be electronically coupled. Furthermore, the inceptor can be back-driven from a host computer. Cockpit sounds (engines, RPM, airspeed, etc.), caution and warnings cues, and pre-recorded voice messages are generated using a MIDI sound simulator. Additional features include dual Control Display Units (CDU's) that can be located either in the center control stand or between the pilot's legs. The RFD has a fully operational Overhead Panel laid out in a configuration similar to a standard B-757. The Center Control Stand has a throttle quadrant similar to a B-777 aircraft and instrumentation common to that class of vehicle. Located in the RFD is a fully functional aircraft radio system including programmable radio heads.

The RFD is one of four simulators designed for use with the Cockpit Motion Facility.

3.3.6 Visual Motion Simulator (VMS).

The VMS is a general-purpose simulator consisting of a two-person cockpit mounted on a six-degree-of-freedom synergistic motion base. The VMS provides a visual out-the-window scene with a FOV of 106 by 36 degrees.

Motion cues are provided in the simulator by computer algorithms which command the relative extension or retraction of the six legs (hydraulic actuators) of the motion base. The visual scene is displayed by means of four display systems which are compatible with the CGI system.

The VMS supports research studies where motion is a critical cue for various types of aircraft or space vehicles. The main instrument panels include six color graphics electronic displays. The cockpit is equipped with programmable control loading systems to provide for roll, pitch, and yaw controls for each crew member. [7,24,27,28,29]

Chapter 4

4 Case Study : Environmental Simulation

The goal of a flight simulator is to simulate flight, i.e. aircrew flight training can be carried out in a flight simulator with such a degree of realism that the aircrew are unaware of the fact that they are in a simulator. To achieve this realism a big amount of hardware and software is required. The simulated aircraft flight compartment is an exact replica of the actual aircraft simulated. It is mounted on the motion system, which gives acceleration cues to the cockpit, and is controlled by an instructor's station. The instructor's station enables the flight instructor to control and monitor all the operations of the simulated flight. It allows the Pilot instructor to witness flight parameters and overall simulation performance as well as modifying them. For example, he can incorporate a malfunction such as Left Engine Failure and then watch on different plots how well the Pilot can keep control of the aircraft under such a condition or he can change the environment conditions during a simulated flight e.g., temperature, QNH, wind speed and wind direction.

During flight simulation, the instructor should be able to set up a specific weather which can help him to fly the aircraft in different scenarios. In weather environment, the following has to be simulated :

- **Ambient Temperature**

  Usually, the static air temperature at the aircraft altitude has standard atmospheric value unless the pilot has selected different input. The selectable inputs are :

  1. Ground temperature
  2. Temperature at an intermediate altitude
  3. Temperature at the tropopause

The temperature at the aircraft shall be linearly interpolated, as a function of aircraft altitude, from these three values.

- **Barometric Pressure**

  Barometric pressure must follow standard atmosphere. The pilot is able to vary sea level barometric pressure from 28.05 to 31.30 inches mercury at 0°C. Changing the sea level pressure shall affect the computation of pressure altitude by algebraically adding an altitude increment.

- **Runway Conditions**

  In addition to dry runways, it should be possible to select water, slush, snow, patchy wet, and patchy ice. These conditions should be reflected in the coefficient of friction of the tires and fluid dynamic drag force variations with ground speed. Thus, the effects representative of stopping and directional control forces should be simulated.

- **Ice Accumulation**

  Icing conditions should be computed when the total air temperature is in the range of +6°C to -20°C, the aircraft is in the clouds and the instructor has selected icing quantities and rates.

- **Wind Shear Effects**

  The effects of three-dimensional wind shear can be simulated by the selection of wind shear profiles summed with the steady-state wind condition derived from wind lapse rate calculations.

- **Turbulence Simulation**

  Turbulence can be divided into three areas :

  1. Low altitude atmospheric turbulence

2. Clear air turbulence
3. Turbulence effects related to thunderstorm activities

The effect of turbulence should be calculated in the mathematical model of the simulated aircraft and introduced through the flight equations. It shall produce the appropriate effects on simulator parameters including airspeed, roll, pitch, angle of attack, sideslip, and rate of climb. The turbulence effects in the cockpit (perceived on instruments, and through motion and visual systems response) are realistically simulated to the satisfaction of the acceptance crew. The motion system shall provide the correct physical sensations which are felt at the onset of acceleration of the simulated aircraft, followed by a low-level acceleration washout.

- **Sounds simulation**

Sound simulation shall be automatic. Sound levels and directions shall be comparable to those found in the actual aircraft.

The following sounds are simulated

1. Thunder noise
2. Wiper noise
3. Crash noise
4. Precipitation noise
5. Sound produced by events and equipment

- **Wind Effects**

It shall be possible for the instructor to set surface wind speed at the airfield from 0 to 100 knots and the surface wind direction through 360 degrees of azimuth. Surface wind shall be the wind speed at 9 meter (30 feet) above ground. Below 9m, the speed shall exponentially decay in a realistic manner. The instructor shall be able to select wind speed from 0 to 300 knots and direction at an intermediate altitude and at the tropopause. Wind speed and wind direction shall be linearly interpolated between these three levels. Above the tropopause, the wind speed and direction shall remain constant. The insertion or modification of wind shall not produce any undesirable transients. It shall be possible for the instructor to monitor the wind speed and direction at the aircraft altitude.

4.1 Simulating wind direction and wind speed

During flight training, the pilot needs to fly the aircraft at different altitude and speed. An instructor station allows him to witness flight parameters and overall simulation performance as well as modifying them. In the appendix wind speed and wind direction are simulated, the pilot can select the wind speed and direction. Some variables are needed to interface with the simulator devices. A graphic page is used to simulate wind speed and wind direction. This page displays a six inch diameter circle on the map representing the current surface wind speed and direction.

The pilot can click on the map, that makes the white arrow moves to the position that he pointed to. This event indicates new wind direction and new speed, the result is displayed on the page by updating the old wind. The pilot also can set the wind speed to zero by clicking on calm wind. Here is a description of each button:

- Wind: Selecting a new wind direction and speed
- Calm wind: Reset wind speed to zero
- OK: Update the new wind (selecting a new wind by clicking on the map)
- Cancel: Cancel the selected new wind

Chapter 5

5. Conclusion.

The use of Flight Simulation is established on a world-wide scale. Without simulators, the economics and safety of Air Transport operations would be compromised. The world's Air Forces increasing rely on simulation for crew training, particularly for aspects which are expensive or difficult to train in the aircraft itself. The design, development and testing of new aircraft uses extensive simulation facilities, thereby enhancing safety, reducing timescales and so, costs. Other applications include research into human factors, and accident investigation.

Simulators are less expensive to operate than all but the simplest aircraft They can be operated at intensive rates by day and night, and can train for any condition, weather, time or location which is included in their data base.

The technology on which flight simulation is based continues to improve, particularly in the fields of computing, graphics, and software. The improvements offer not only more cost-effective simulator training, but also scope to use simulators in new applications, and to reduce further the cost of training in both civil and military aircraft.

These benefits will only be fully realized when the work is carried out to incorporate improvements in existing systems and to apply new technologies to flight simulation. In the past, the UK has played a central role in such work, through industry, some universities and the MoD Research Establishments. It is less clear today how such work is to be done, due both to contraction in defense-related industry, and to the overall economic situation. Flight Simulation has proved its value in both commercial and military aviation and there is a well-established industry in the development and production of such simulators.

Chapter 6

6. The future of flight simulation.

In near future, we wish to look at the current capabilities of flight simulation, which is acknowledged as a very powerful technology. we will also question whether current technology is providing for the needs of all customers including civil, military, R&D, engineering, etc. Some thoughts include: Descriptions of the latest technology and future possibilities in particular areas. Are customers and potential customers taking advantage of what is currently possible using the latest advances in simulation technology? Will advances in flight simulation improve customers' capabilities and prove cost-effective? Is flight simulator technology and design led by the technology, by customer needs, or by the regulators, both civil and military? Are there needs which are not currently addressed? Where should future research and development be aimed? Do some people have the wrong idea about using this powerful technology?

Papers are sought on all aspects of flight simulation and might include:

<u>Image Generation</u>

- Developments in image generation
- Wide area geospecific imagery with high fidelity
- Sources and integration for high resolution geospecific imagery
- Image generation for the civil role
- Image generation for the nap-of-the-earth helicopter role
- The need or otherwise for high resolution
- Have visual databases gone too far? Do we need this level of fidelity?

Display Systems

- Developments in display technology
- Optimal fields of view for display systems and how these vary with the role
- The challenge of vertical field of view
- The need for collimation - is it conditional on type of training?
- Collimation versus vertical field of view
- Domes - the way ahead?
- Does the head-mounted display have a real role or is it a gimmick?
- Can display technology match that of image generation?

Motion Cueing

- Optimization of motion cueing
- Progress in platform design
- Is there a case for fewer degrees of freedom in motion for specified training tasks?
- Is there a minimum acceptable specification for motion systems?
- Cueing for military manoeuvres including high
- Can the motion seat replace the platform?
- Fighter simulators do not need motion
- Fighter simulators need motion just like the others

Training

- Mission simulation
- Helicopter simulation - the last frontier?
- Emergencies and failures - how well can simulation train for them?
- The use and capabilities of lesson plans
- Forward facing instructor operating stations pros and cons

- Instructor operating stations - malfunction simulation
- Control of complex military simulations for optimal training value
- Developing battlefield tactics using simulation
- Battlefield command training - what is the limit?
- Can simulation train the battlefield commander?

Synthetic Environments

- Application of synthetic environments to flight simulation
- Are synthetic environments a temporary fad?
- Synthetic environments - how realistic can we get? And how realistic do we need to get?

Networking

- War gaming simulations
- Integration of flight simulators, battlefield models, and real vehicles
- Is there value in networking of commercial simulators?

R&D and Engineering Applications

- Developments in simulation for R&D
- Developments in engineering simulation
- Why the simulator is needed before the aircraft
- Can engineering simulator data replace flown data? [12,15,16,18,19,22,24,27,34]

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Appendix

The function wind & speed direction

```
int wind_speed_direction()
{
#define MAP_WIND_WIN    POP_WIND
#define MAP_WIND_PAGE   1
#define MAX_XY          650
#define OUTTER_RADIUS   MAX_XY/2
#define INNER_RADIUS    80
#define INNER_CIRCLE_R  75
#define MAX_SPEED       50
#define VALID_AREA      OUTTER_RADIUS
#define                                              SPEED_RATIO
(((float)(MAX_SPEED))/((float)(VALID_AREA)))
#define  SPEED_TRUE_RATIO  ((float)  MAX_SPEED  /  (float)
(OUTTER_RADIUS-INNER_RADIUS))
#define                                         TRUE_SPEED_RATIO
(((float)(MAX_SPEED))/((float)(VALID_AREA-
INNER_CIRCLE_R)))
#define  DEFAULT_RADIUS       (((float)INNER_CIRCLE_R)  /
((float)OUTTER_RADIUS))

  int   x_pos;
  int   y_pos;
  int   theta_new;
  static  int   theta_old;
  int    theta_flight;
  float  ftheta_new;
  float temp, ttemp;
  float radius_new;
  float radius_check;
  static  float radius_old;
  float speed, tspeed;
  static  int   old_tmmxwind = FALSE;

  static int Tid_tzchatm;
  static int Tid_tmfwdir;
  static int Tid_tmfwspd;
  static int first_pass = TRUE;

  if (first_pass) {
    first_pass = FALSE;
  }

  if (xopage[MAP_WIND_WIN] == MAP_WIND_PAGE )
     tmmxwind = TRUE;


  if (!old_tmmxwind && tmmxwind) {
    tmfwdir    = 0;
    tmfwspd    = 0;
    tmmwaold   = 0.0;
```

```
    if (H_tmmwspd == 0.0){
      tmmwrold = DEFAULT_RADIUS;
    }else{


      tmmwrold = ((float) H_tmmwspd / (float) MAX_SPEED)
+ DEFAULT_RADIUS;

    }

    tmmwanew = 0;
    tmmwrnew = 0;

    tmmwxin   = 0;
    tmmwyin   = 0;

  }
  old_tmmxwind = tmmxwind;

  if (!tmmxwind)
    return 0;

  if (tmmxentr) {

    tzchatm = TRUE;
    tmmxwind = FALSE;
    tmmxentr = FALSE;
    tmmwrold = tmmwrnew;
  }

  if (tmmxcanc) {
    tmmxwind = FALSE;
    tmmxcanc = FALSE;
  }


  /* Set up old parameters: */
  theta_old = 90 - H_tmmwdir;
  if (theta_old < 0 ) theta_old = 360 + theta_old;

  radius_old  =  (float)  H_tmmwspd  /  TRUE_SPEED_RATIO  /
((float) OUTTER_RADIUS) +
               DEFAULT_RADIUS;

  tmmwaac   = 90 - H_tmmachdg;
  if (tmmwaac <  0 ) tmmwaac = 360 + tmmwaac;
  tmmwaold = theta_old;      /* old vector angle      */
  tmmwrold = radius_old;     /* old vector radius     */

  if ((tmmwxin==0)&&(tmmwyin==0)){
    return 0;
  }
  x_pos = tmmwxin - OUTTER_RADIUS;
  y_pos = tmmwyin - OUTTER_RADIUS;
  /*
   CALCULATE the angle of the vector w.r.t. the positive
x-axis,
```

```
     counter-clockwise rotation. (min = 0, max = 359)
   */

   if         ((x_pos == 0) && (y_pos >  0))   {
     theta_new = 90;

   } else if ((x_pos == 0) && (y_pos <  0))   {
     theta_new = 270;
   } else if ((y_pos == 0) && (x_pos <  0))   {

     theta_new = 180;
   } else if ((y_pos == 0) && (x_pos >  0))   {
     theta_new = 0;
   } else if ((x_pos == 0) && (y_pos == 0))   {
     theta_new = 0;
   } else {
     temp        = (float)  ( (float) abs(y_pos)  /  (float)
abs(x_pos) );
#ifdef WIN32
     theta_new = (int)(RAD2DEG(atan((float) temp)));
#else
     theta_new = RAD2DEG(fatan((float) temp));
#endif
     if         ((x_pos < 0) && (y_pos > 0)) {
       theta_new = 180 - theta_new;
     } else if ((x_pos < 0) && (y_pos < 0)) {
       theta_new = 180 + theta_new;
     } else if ((x_pos > 0) && (y_pos < 0)) {
       theta_new = 360 - theta_new;
     } else if ((x_pos > 0) && (y_pos > 0)) {
       theta_new = 000 + theta_new;
     }
   }
   ftheta_new = (float)DEG2RAD(theta_new);

   /*
    CALCULATE  the  flight  wind  direction  w.r.t.  positive
y-axis,
    clockwise rotation. (min = -180, max = 180 ).
   */

   theta_flight = 90 - theta_new;
   if   (theta_flight   <   -180)   theta_flight   =   360   +
theta_flight;

   /*
    CALCULATE the wind spd radius and value.
   */

   temp   = ((float)(y_pos*y_pos)+(float)(x_pos*x_pos));
#ifdef WIN32
   speed   = (float) sqrt( (double) temp);
   ttemp                    =                   ((float)(y_pos-
(float)INNER_CIRCLE_R*sin(ftheta_new))*
                    (y_pos-
(float)INNER_CIRCLE_R*sin(ftheta_new))) +
            ((float)(x_pos-
(float)INNER_CIRCLE_R*cos(ftheta_new))*
```

```
                    (x_pos-
(float)INNER_CIRCLE_R*cos(ftheta_new)));

  tspeed = (float) fsqrt((float)ttemp);
#else

  speed  = (float) fsqrt( (float) temp);
  ttemp              =                ((float)(y_pos-
(float)INNER_CIRCLE_R*fsin(ftheta_new))*


                    (y_pos-
(float)INNER_CIRCLE_R*fsin(ftheta_new))) +
          ((float)(x_pos-
(float)INNER_CIRCLE_R*fcos(ftheta_new))*
                    (x_pos-
(float)INNER_CIRCLE_R*fcos(ftheta_new)));

  tspeed = (float) fsqrt((float)ttemp);
#endif
  if (speed > OUTTER_RADIUS) return 0;

  radius_new    =    ((float)    speed)    /    ((float)
OUTTER_RADIUS);
  radius_check   =   ((float)INNER_CIRCLE_R   +   0.5)   /
((float) OUTTER_RADIUS);

  if (radius_new < radius_check) {
    radius_new = radius_check;
    tspeed = 0.0;
    speed  = 0.0;
  }else{
    tspeed     = (float)(tspeed*TRUE_SPEED_RATIO);
  }

  tmmwxin   = 0;                      /* x-pos input (0-650)
*/
  tmmwyin   = 0;                      /* y-pos input (0-650)
*/
  tmmwxzr   = 0;                     /* x-pos output must =0
*/
  tmmwyzr   = 0;                     /* y-pos output must =0
*/

  tmmwanew  =  theta_new;              /*  new  vector  angle
*/
  tmmwaold  =  theta_old;              /*  old  vector  angle
*/
  tmmwrnew  =  radius_new;            /*  new  vector  radius
*/
  tmmwrold  =  radius_old;            /*  old  vector  radius
*/
  tmfwdir   =  theta_flight;        /*  new  wind  direction
*/
  tmfwspd   =  tspeed;                   /*  new  wind  speed
*/
  return 0;
}
```

The header file that contains the variables to communicate with the simulator

```
extern struct cdb_xrftest {
 unsigned char  dum0000001[71600];
 double         _vpsidg;          /* HEADING EULER A */
 unsigned char  dum0000002[254848];
 double         _ruplat;          /* A/C LATITUDE    */
 double         _ruplon;          /* A/C LONGITUDE   */
 unsigned char  dum0000003[472];
 float          _rtavar;          /* MAGNETIC VARIAT */
 unsigned char  dum0000004[726136];
 unsigned char  _tcmrphdg;        /* REPOSITION HDG  */
 unsigned char  dum0000005[1];
 unsigned char  _tcmrpmch;        /* MACH NUMBER SET */
 unsigned char  dum0000006[1];
 unsigned char  _tcmrpalt;        /* REPOS ALT SELEC */
 unsigned char  _tcmrpspd;        /* REPOS SPD SELEC */
 unsigned char  dum0000007[102041];
 unsigned char  _tcmexecav;       /* EXEC FEATURE ON */
 unsigned char  dum0000008[412];
 float          _tawspd[8];       /* WIND SPEED AT F */
 float          _tawdir[8];       /* WIND DIRECTION  */
 unsigned char  dum0000009[2360];
 float          _tarepalt;        /* REPOSITION ALTI */
 float          _tarepspd;        /* REPOSITION SPEE */
 float          _tarephdg;        /* REPOSITION HEAD */
 unsigned char  dum0000010[4];
 float          _tarepmch;        /* MACH NUMBER FOR */
 unsigned char  dum0000011[20308];
 float          _tarepaltmin;     /* MINIMUM ALTITUD */
} xrftest;
static struct cdb_xrftest *yxrftest = &xrftest;
#define vpsidg                           (xrftest._vpsidg)
#define ruplat                           (xrftest._ruplat)
#define ruplon                           (xrftest._ruplon)
#define rtavar                           (xrftest._rtavar)
#define tcmrphdg                         (xrftest._tcmrphdg)
#define tcmrpmch                         (xrftest._tcmrpmch)
#define tcmrpalt                         (xrftest._tcmrpalt)
#define tcmrpspd                         (xrftest._tcmrpspd)
#define tcmexecav                        (xrftest._tcmexecav)
#define tawspd                           (xrftest._tawspd)
#define tawdir                           (xrftest._tawdir)
#define tarepalt                         (xrftest._tarepalt)
#define tarepspd                         (xrftest._tarepspd)
#define tarephdg                         (xrftest._tarephdg)
#define tarepmch                         (xrftest._tarepmch)
#define tarepaltmin                      (xrftest._tarepaltmin)

extern struct cdb_xrftest6 {
 unsigned char  dum0600001[1464];
 short          _xopage[32];     /* PAGE REQUESTED  */
 unsigned char  dum0600002[20533];
 unsigned char  _tmmxwind;       /* MAP CURSOR MODE */
 unsigned char  dum0600003[5];
 unsigned char  _tmmxcanc;       /* MAP CURSOR MODE */
```

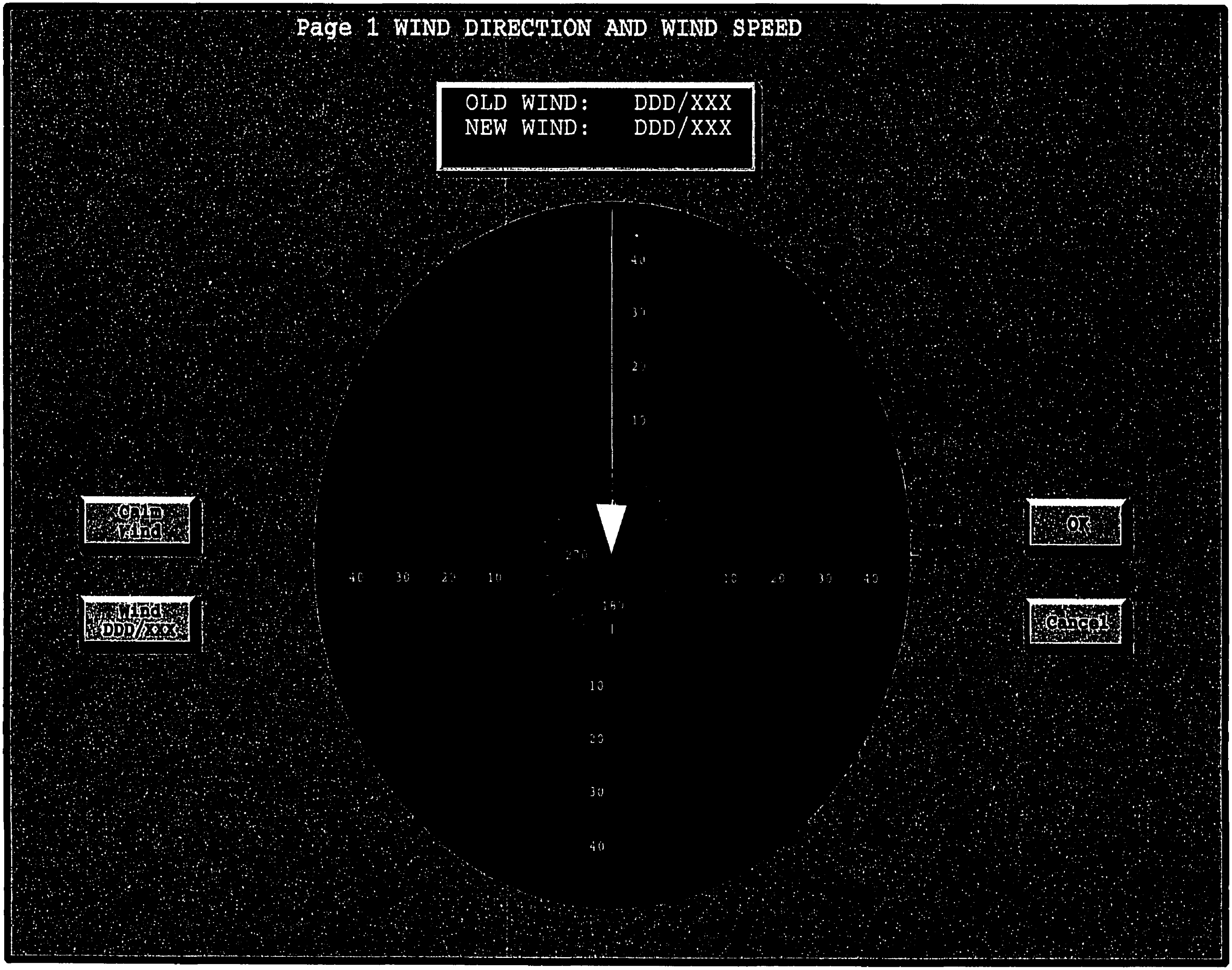
```
  unsigned char  dum0600004[1];
  unsigned char  _tmmxentr;        /* MAP CURSOR MODE */
  unsigned char  dum0600005[46];

  float          _tmfwdir;         /* WIND  new wind   */
  float          _tmfwspd;         /* WIND  old wind   */
  short          _tmmwxin;         /* WIND  x-input f  */
  short          _tmmwyin;         /* WIND  y-input f  */
  short          _tmmwyzr;         /* WIND  sets the   */
  short          _tmmwxzr;         /* WIND  sets the   */
  short          _tmmwanew;        /* WIND  new angle */
  short          _tmmwaold;        /* WIND  old angle */
  short          _tmmwaac;         /* WIND  A/C ANGLE */
  unsigned char  dum0600006[2];
  float          _tmmwrnew;        /* WIND  new radiu */
  float          _tmmwrold;        /* WIND  old radiu */
  unsigned char  dum0600007[16147];
  unsigned char  _tzchatm;         /* FB FLAG FOR TCM */
  float          _tzfbhdg;         /* FEAD BACK VALUE */
  unsigned char  dum0600008[20];
  unsigned char  _tzexecslw;       /* EXECUTE ALT/IAS */
  unsigned char  _tz0execslw;      /* EXECUTE ALT/IAS */
  unsigned char  _tzcanslw;        /* CANCEL ALT/IAS/ */
  unsigned char  dum0600009[1];
  float          _tzrepalt;        /* REPOSITION GRAP */
  unsigned char  _tzrepaltf;       /* REPOSITION GRAP */
  unsigned char  dum0600010[3];
  float          _tzrepspd;        /* REPOSITION GRAP */
  unsigned char  _tzrepspdf;       /* REPOSITION GRAP */
  unsigned char  dum0600011[3];
  float          _tzhdgslac;       /* HEADING SLEW A/ */
  unsigned char  dum0600012[1];
  unsigned char  _tzhdgslhs;       /* HEADING SLEW HA */
  unsigned char  dum0600013[6];
  double         _tzreplat;        /* REPOSITION LATI */
  double         _tzreplon;        /* REPOSITION LONG */
  float          _tzrepmac;        /* REPOSITION MACH */
  unsigned char  _tzrepposf;       /* REPOSITION LAT/ */
  unsigned char  _tzrepmacf;       /* REPOSITION MACH */
  unsigned char  dum0600014[1];
  unsigned char  _tzrepnq;         /* REPOSITION - NO */
} xrftest6;
static struct cdb_xrftest6 *yxrftest6 = &xrftest6;
#define xopage                    (xrftest6._xopage)
#define tmmxwind                  (xrftest6._tmmxwind)
#define tmmxcanc                  (xrftest6._tmmxcanc)
#define tmmxentr                  (xrftest6._tmmxentr)
#define tmfwdir                   (xrftest6._tmfwdir)
#define tmfwspd                   (xrftest6._tmfwspd)
#define tmmwxin                   (xrftest6._tmmwxin)
#define tmmwyin                   (xrftest6._tmmwyin)
#define tmmwyzr                   (xrftest6._tmmwyzr)
#define tmmwxzr                   (xrftest6._tmmwxzr)
#define tmmwanew                  (xrftest6._tmmwanew)
#define tmmwaold                  (xrftest6._tmmwaold)
#define tmmwaac                   (xrftest6._tmmwaac)
#define tmmwrnew                  (xrftest6._tmmwrnew)
```

```
#define tmmwrold                          (xrftest6._tmmwrold)
#define tzchatm                           (xrftest6._tzchatm)
#define tzfbhdg                           (xrftest6._tzfbhdg)


#define tzexecslw                         (xrftest6._tzexecslw)
#define tz0execslw                        (xrftest6._tz0execslw)
#define tzcanslw                          (xrftest6._tzcanslw)
#define tzrepalt                          (xrftest6._tzrepalt)
#define tzrepaltf                         (xrftest6._tzrepaltf)
#define tzrepspd                          (xrftest6._tzrepspd)
#define tzrepspdf                         (xrftest6._tzrepspdf)
#define tzhdgslac                         (xrftest6._tzhdgslac)
#define tzhdgslhs                         (xrftest6._tzhdgslhs)
#define tzreplat                          (xrftest6._tzreplat)
#define tzreplon                          (xrftest6._tzreplon)
#define tzrepmac                          (xrftest6._tzrepmac)
#define tzrepposf                         (xrftest6._tzrepposf)
#define tzrepmacf                         (xrftest6._tzrepmacf)
#define tzrepnq                           (xrftest6._tzrepnq)
/* C---------------------------------------------------*/

#define H_tmmwspd      tawspd[1]
#define H_tmmwdir      tawdir[1]
#define H_tmmachdg     vpsidg
```


Page 1 WIND DIRECTION AND WIND SPEED
OLD WIND: DDD/XXX
NEW WIND: DDD/XXX
Calm Wind
Wind DDD/XXX
OK
Cancel
40
30
20
10
10
20
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40